Performance comparisons

Neutrino factory:

10^{21} muon decays per year (half of each sign)
MagIronNeutrinoDetector 50kton@4000km and 7000 km
mu thresh: Hard (4 GeV) 50 GeV Nufact
or low cut (L>75cm of iron) and 20 GeV Nufact

2.5% signal efficiency error and 20% error on bkg
1% error on matter effect.

Beta-beam

2.9 10^{18} He and 1.1 10^{18} Ne decays/year high or low γ
500kton Water Cherenkov 130 km for γ=100; 730 km for γ=350
2% global normalization
1% neutrino to anti neutrino ratio

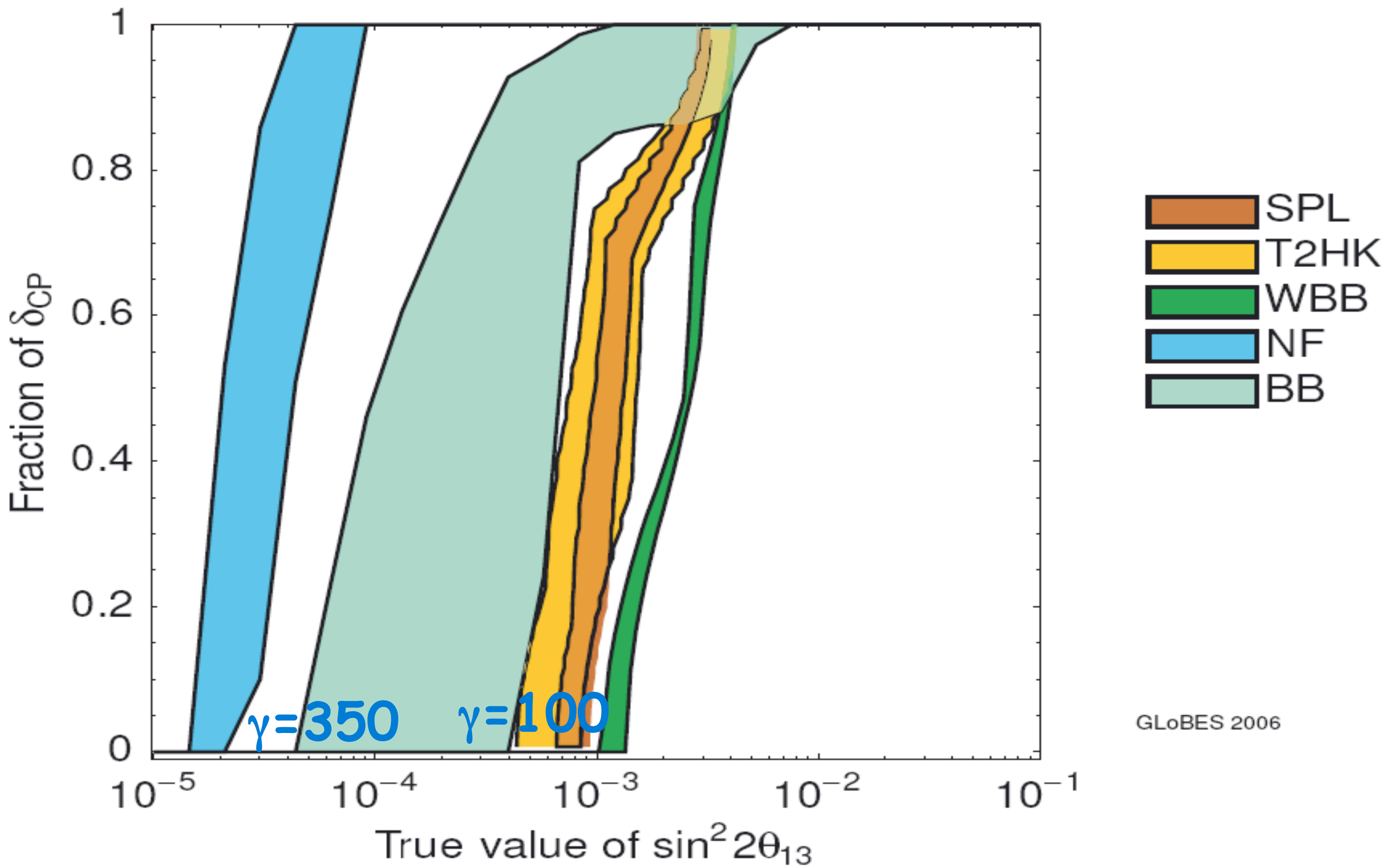


Figure 103: The discovery reach of the various proposed facilities in $\sin^2 2\theta_{13}$. In the area to the right of the bands, $\sin^2 2\theta_{13} = 0$ can be excluded at the 3σ confidence level. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ ('Fraction of $\delta_{\rm CP}$') and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to the conservative set-ups while the left-hand edges correspond to the optimised set-ups, as described in the text. The discovery reach of the SPL super-beam is shown as the orange band, that of T2HK as the yellow band, and that of the wide-band beam experiment as the green band. The discovery reach of the beta-beam is shown as the light green band and the Neutrino Factory discovery reach is shown as the blue band.

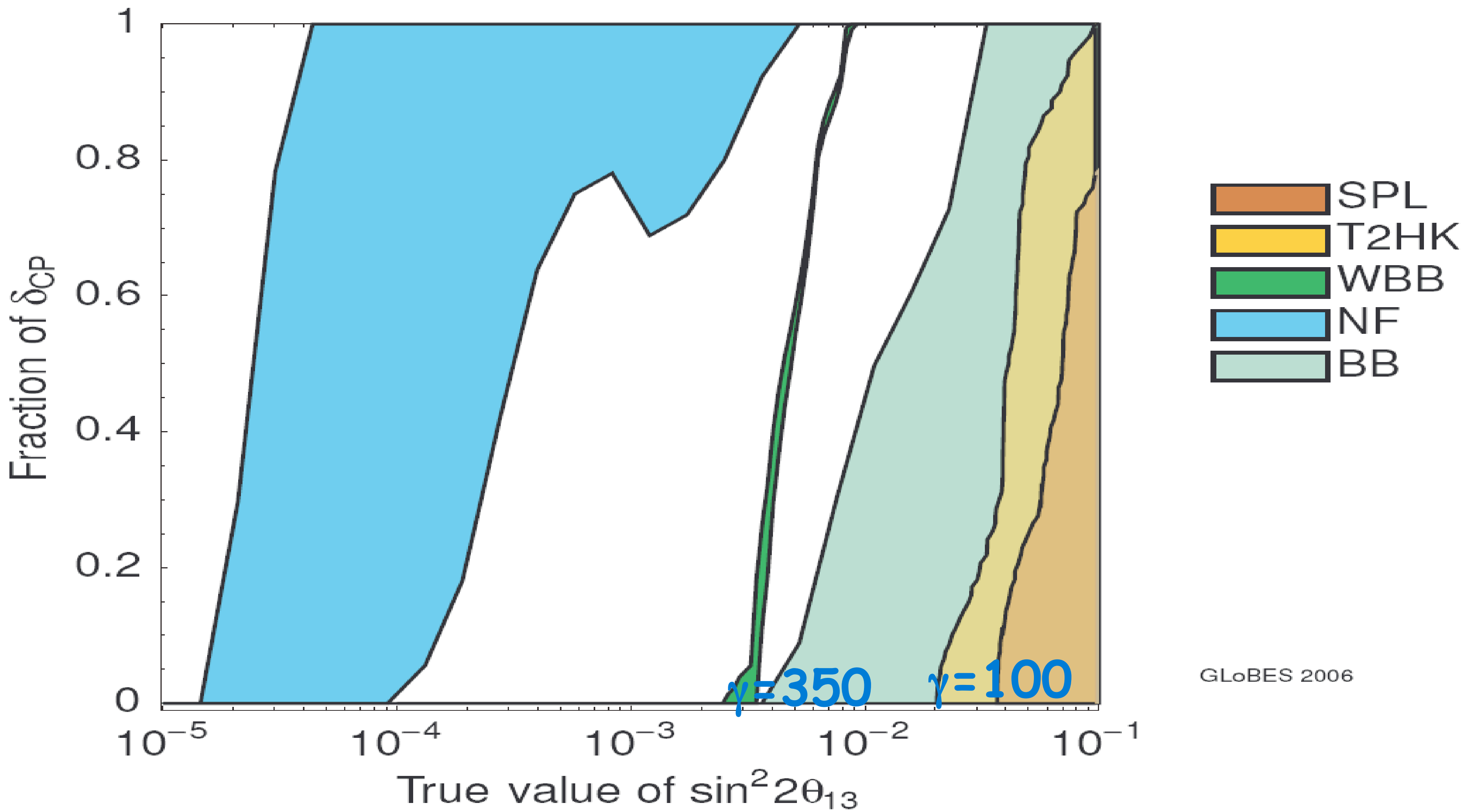


Figure 104: The discovery reach of the various proposed facilities for the discovery of the mass hierarchy. In the area to the right of the bands, signΔm^2_{31} can be established at the 3σ confidence level. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ ('Fraction of δ_{CP}') and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to the conservative set-ups while the left-hand edges correspond to the optimised set-ups, as described in the text. The discovery reach of the SPL super-beam is shown as the orange band, that of T2HK as the yellow band, and that of the wide-band beam experiment as the green band. The discovery reach of the beta-beam is shown as the light green band and the Neutrino Factory discovery reach is shown as the blue band.

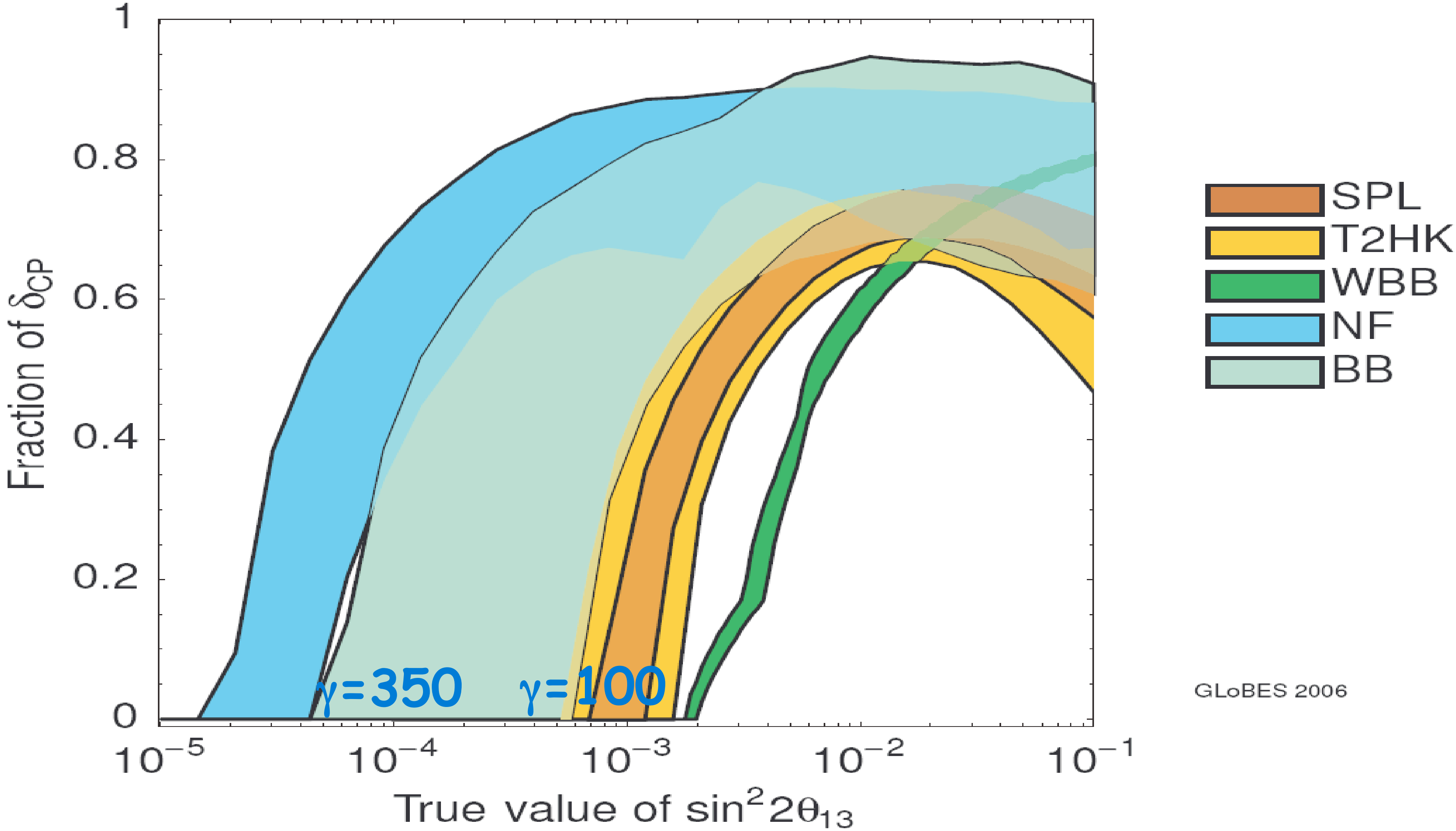


Figure 105: The discovery reach of the various proposed facilities in the CP phase δ. In the area to the right of the bands, $\delta = 0$ and $\delta = \pi$ can be excluded at the 3σ confidence level. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ ('Fraction of δ_{CP}') and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to the conservative set-ups while the left-hand edges correspond to the optimised set-ups, as described in the text. The discovery reach of the SPL super-beam is shown as the orange band, that of T2HK as the yellow band, and that of the wide-band beam experiment as the green band. The discovery reach of the beta-beam is shown as the light green band and the Neutrino Factory discovery reach is shown as the blue band.

NEUTRINO FACTORY DETECTORS

An ideal detector exploiting a Neutrino Factory should:

Identify and measure the charge of the muon ("golden channel") with high accuracy and efficiency

Identify and measure the charge of the electron with high accuracy ("Platinum channel")

Identify the τ decays ("silver channel")

Measure the complete kinematics of an event in order to increase the signal/back ratio

-- Magnetized Iron Neutrinofactory Detector*)

this is a typical NUFACT detector for E_ν>1.5 GeV $\nu_e \rightarrow \nu_\mu$

GOLDEN CHANNEL

experience from MINOS & NOvA
designs prepared for Monolith and INO

iron-scintillator sandwich with sci-fi + APD read-out

proposed straightforward design 100kton for ~200-300M$ (Nelson)

*) MIND

Magnetized Iron calorimeter

(baseline detector, Cervera, Nelson)

$B = 1.7$ T $\Phi = 15$ m, $L = 25$ m

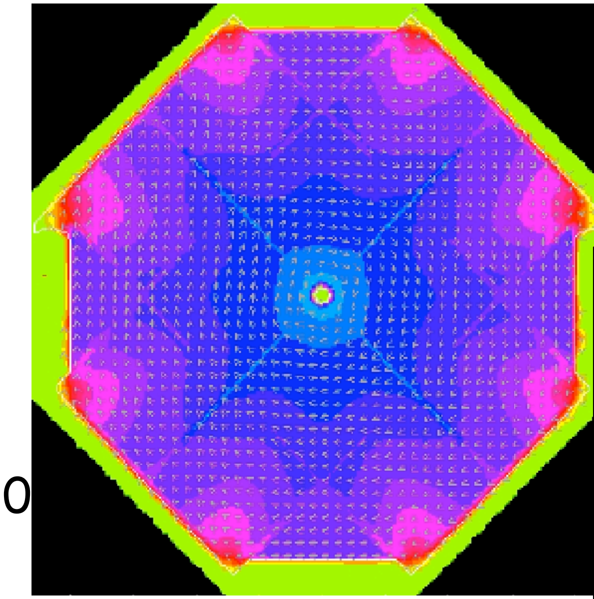
t(iron) =4cm, t(sc)=1cm

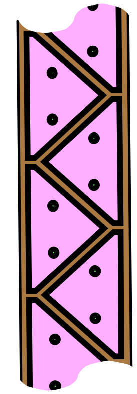
Fiducial mass = 100 kT

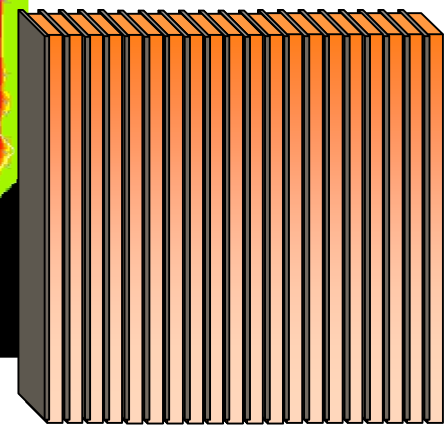
Charge discrimination down to 1 GeV

very similar to MINOS/NOvA/ND280

ex. detector: sci. fi. detector with multipixel APD readout



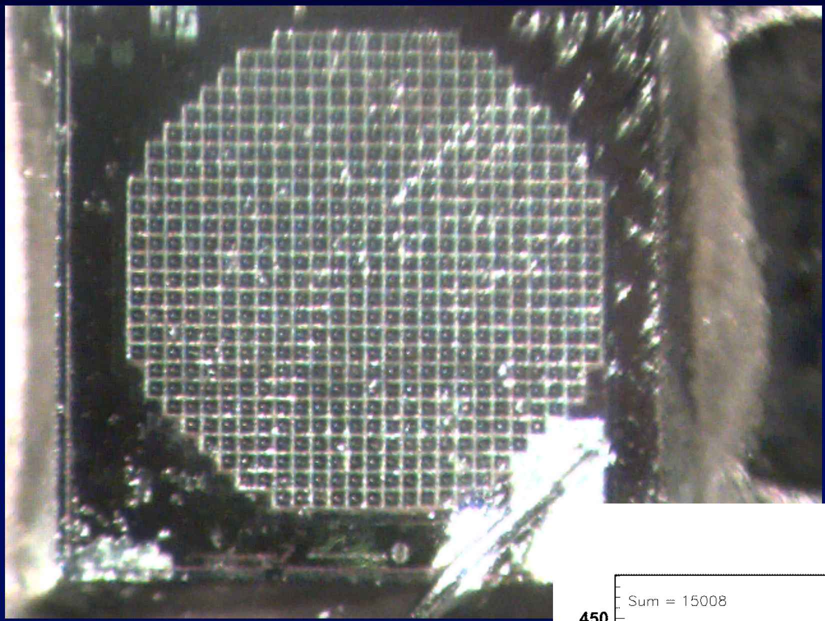


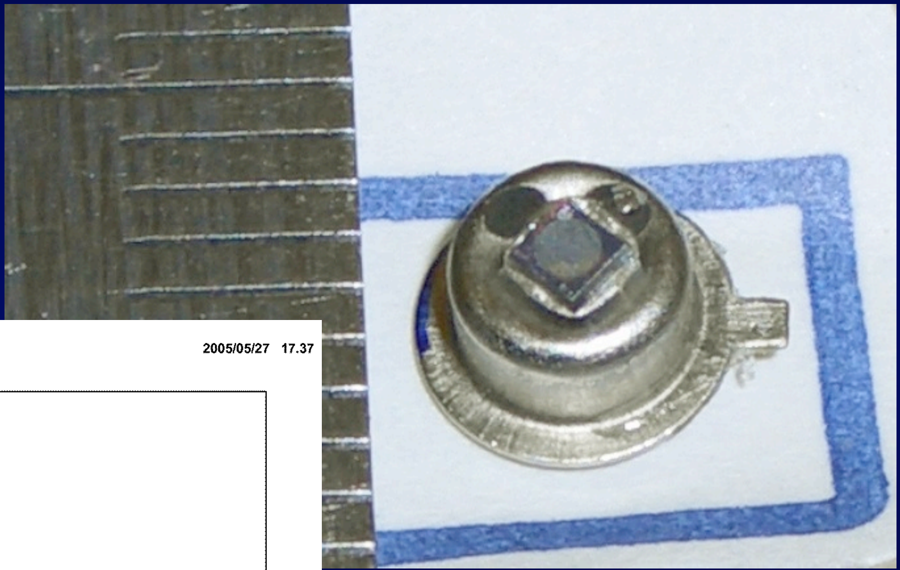


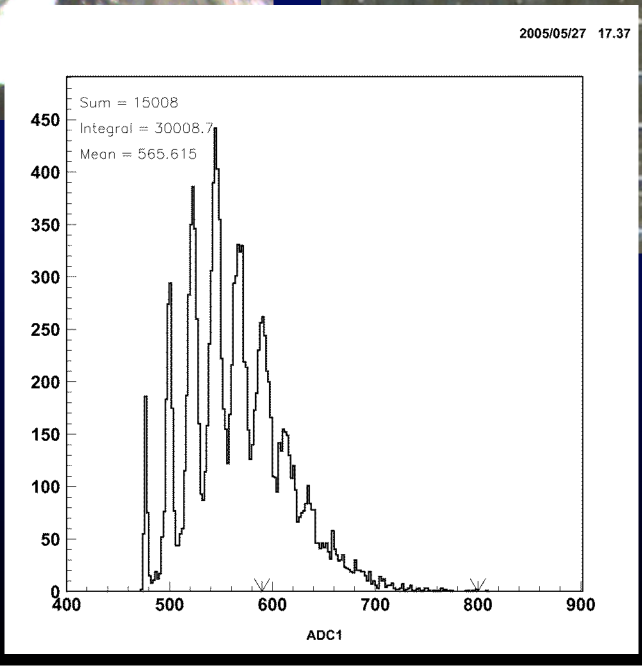
Event rates for 10^{21} muon decays for 50 GeV beam

Baseline	$\bar{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2\theta_{13}=0.01$)	
732 Km	10^9	2×10^9	3.4×10^5	(J-PARC I→ SK = 40)
3500 Km	4×10^7	7.5×10^7	3×10^5	

Multi-Pixel-Photon-Counter Operation



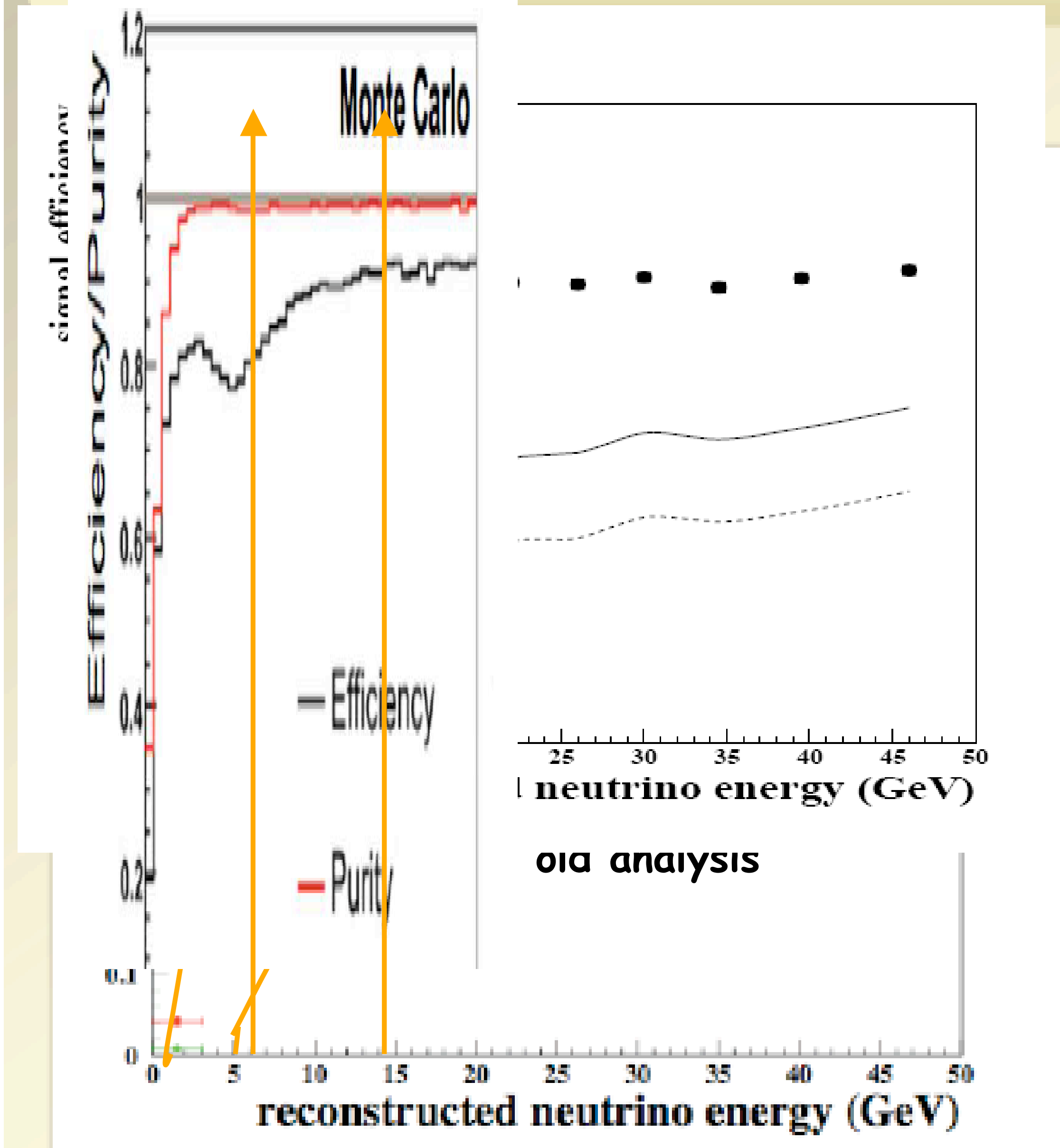




baseline detectors for T2K ND280 detectors!

Kudenko

: signal efficiency



New analysis (Cervera)

OLD: P_μ > 5 GeV

NEW: $L_\mu > L_{had}$ + 75cm

(shown for three different purity levels down to << 10^{-4})

probably underestimated efficiency in GeV region should be fully evaluated with QE included.

NB performance of INO should be similarly evaluated

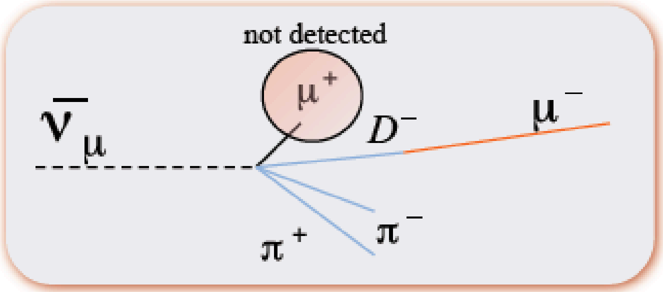
$\bar{\nu}_\mu$CC background

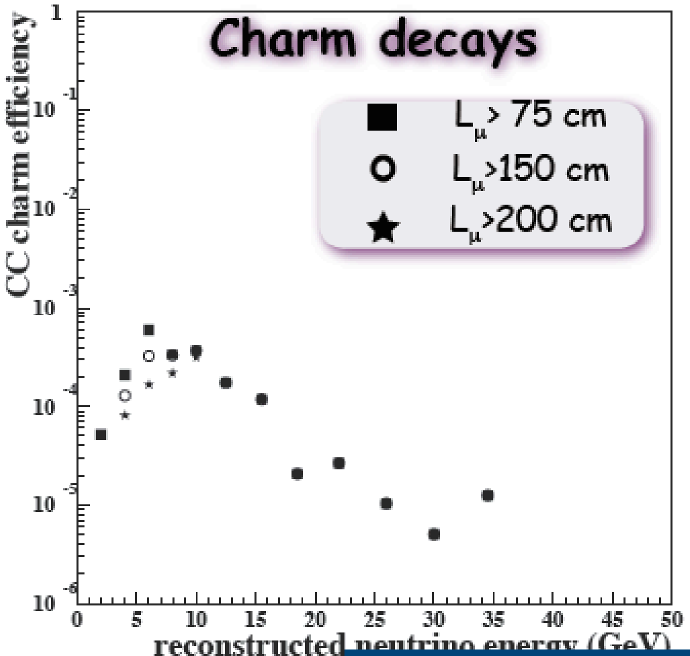
The primary muon is not detected:

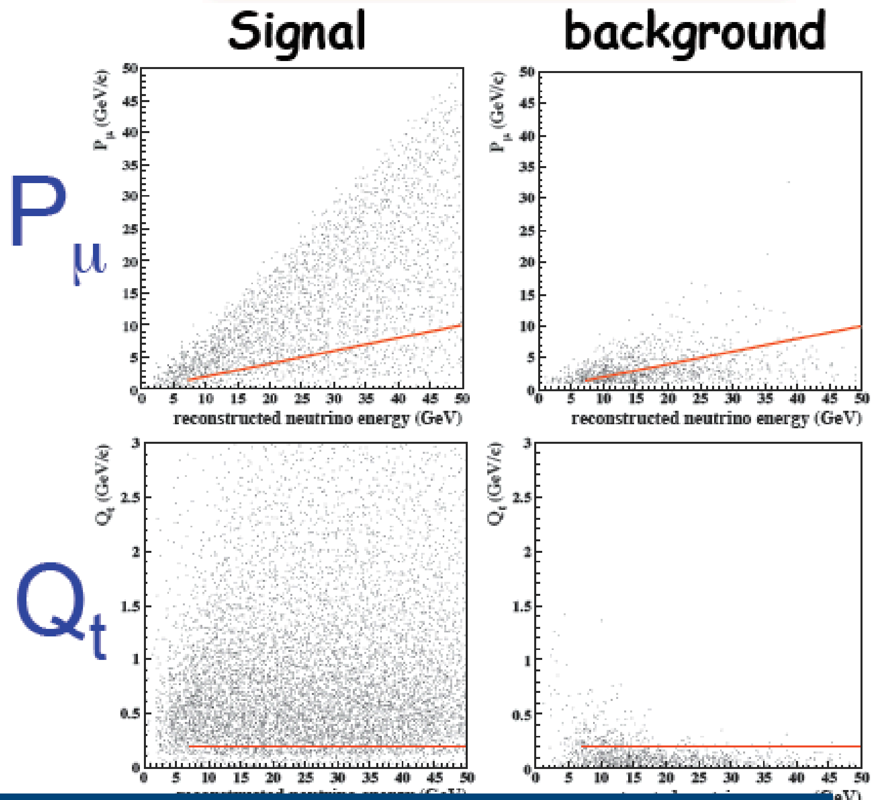
$L_{\mu+}-L_{had} < 75$ cm

A negative muon from hadron decay passes the muon id criterion:

$L_{\mu-}-L_{had} > 75$ cm



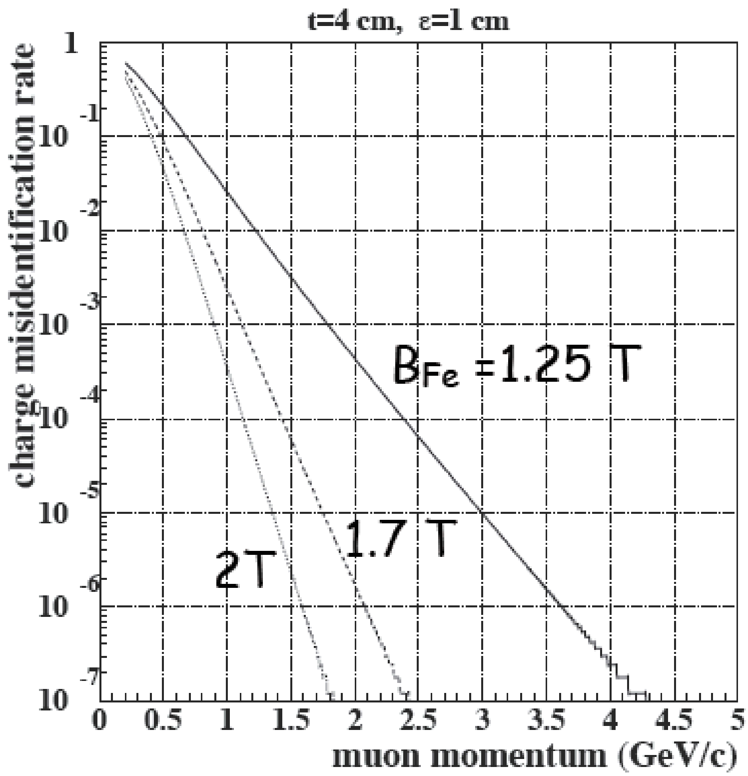




Background is at the level of a few 10^{-4}

Charge identification

- This is the main problem at low energies
- Simple exercise. Assumptions:
  - No border effects
  - Non-gaussian scatters can be identified via local χ^2 criterion with a Kalman Filter
    - Assume gaussian MS
  - Use Gluckstern formula + MS term

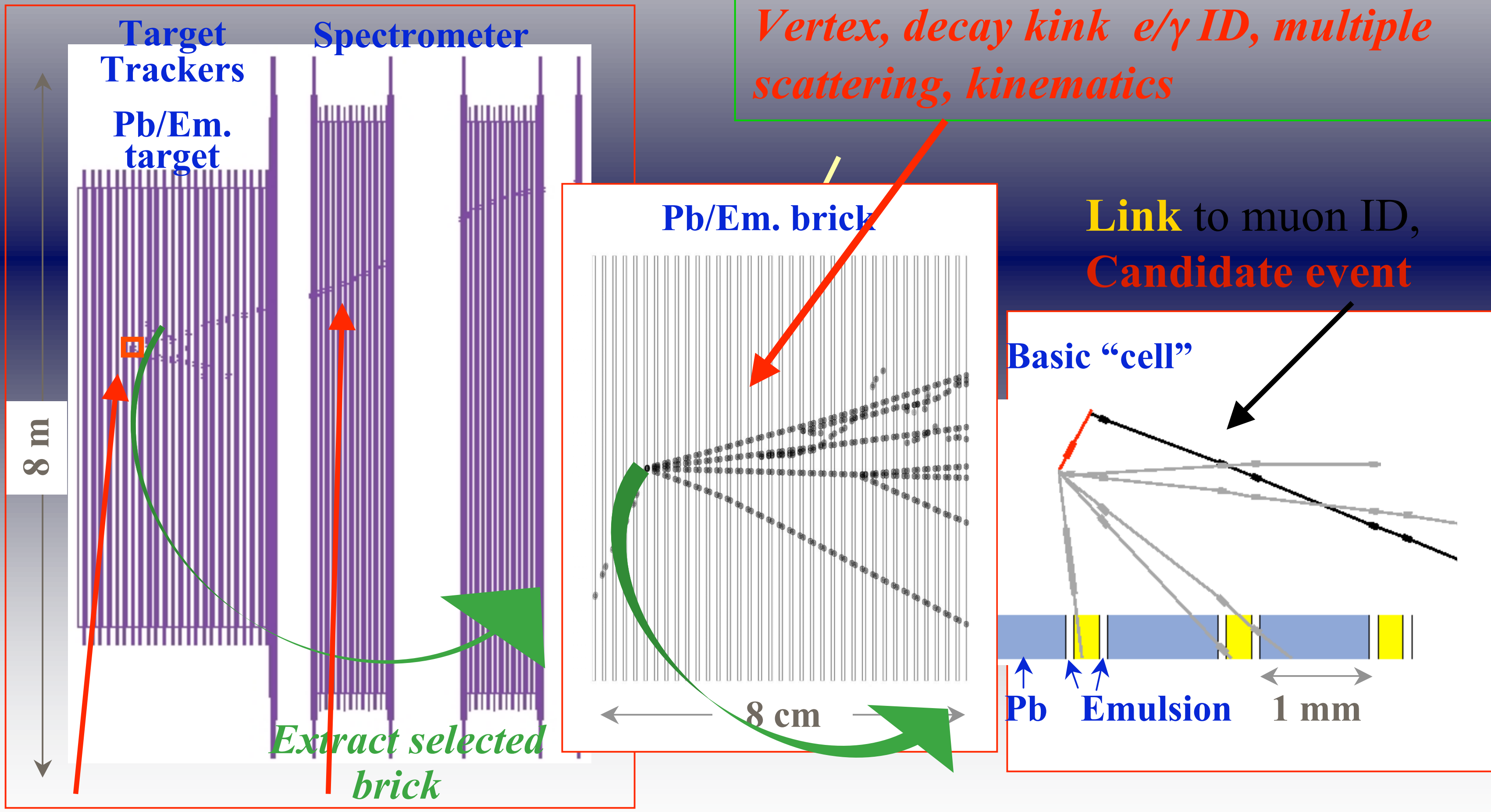


BASELINE SILVER DETECTOR

Electronic detectors:

ECC emulsion analysis:

Vertex, decay kink e/γ ID, multiple scattering, kinematics



Brick finding, muon ID, charge and p $\Delta p/p < 20\%$

LARGE MAGNETIC VOLUME

MIND + emulsions provide
golden
+ **silver** with low efficiency (muon decays)

these are feasible and of established performance.

Observing the **platinum** channel $\nu_{\mu} \rightarrow \nu_{e}$

or the **silver** channel $\nu_{e} \rightarrow \nu_{\tau}$ for more decay channels

requires a dedicated

Low Z and very fine grained detector immersed in a large magnetic volume (CF NOMAD)

Large magnetic volume

A Bross et al see appendix B

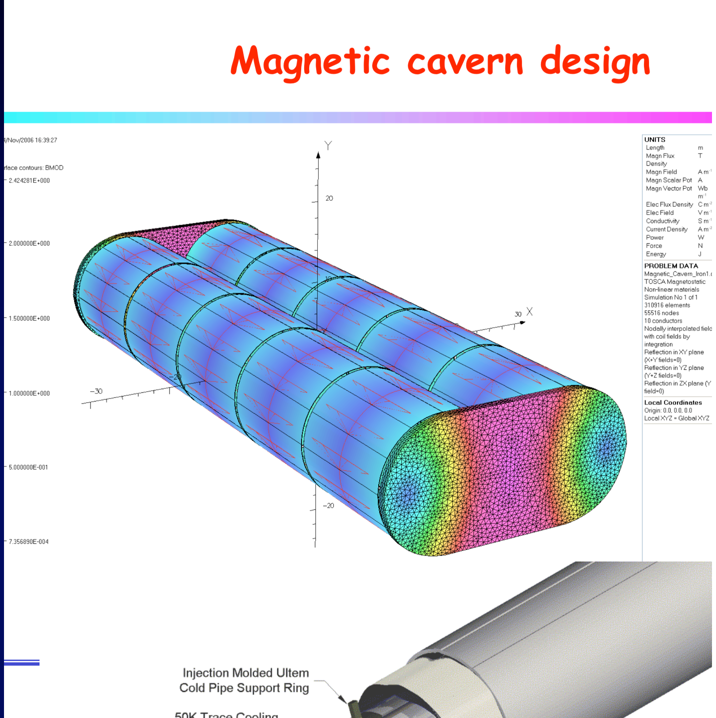
Question: how to equip a volume of ~20-50kton of fine grained scintillator (TASD or Liquid Argon) with a magnetic field that is sufficient to measure electron charge up to sufficient momentum ?

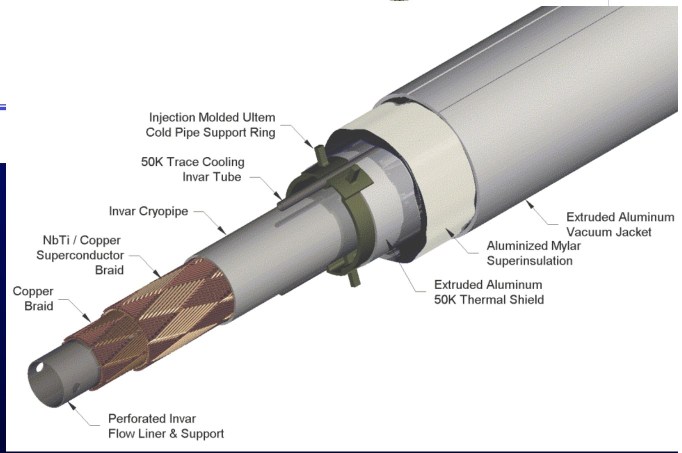
Conventional coils (aluminum)
power consumption is large (200M$/10 yrs)!

Conventional supra:
construction cost is prohibitive
(140-600 M$depending on cost model)
dominated by cost of cryostat to resist forces.

Superconducting Transmission Line (using study for VLHC)
(SC cable inside a 4K cryopipe) could be affordable
For 30-60 kton detector.

High Tc (useful for Larg TPC) not feasible today,
but in 10 yrs? (See later for LArg)





Totally Active Scintillator Detector

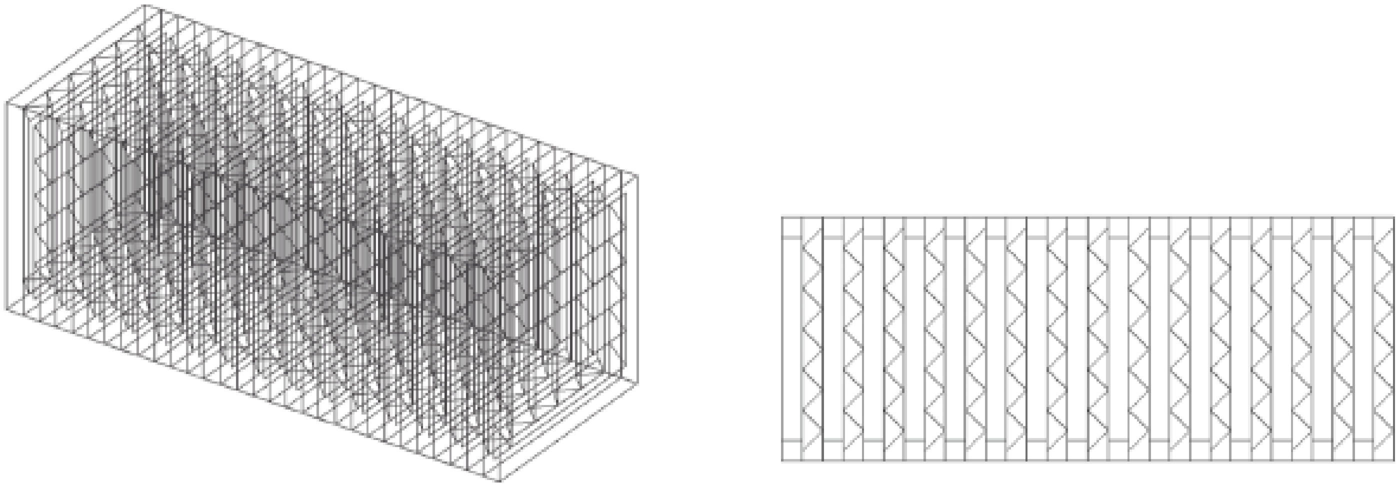


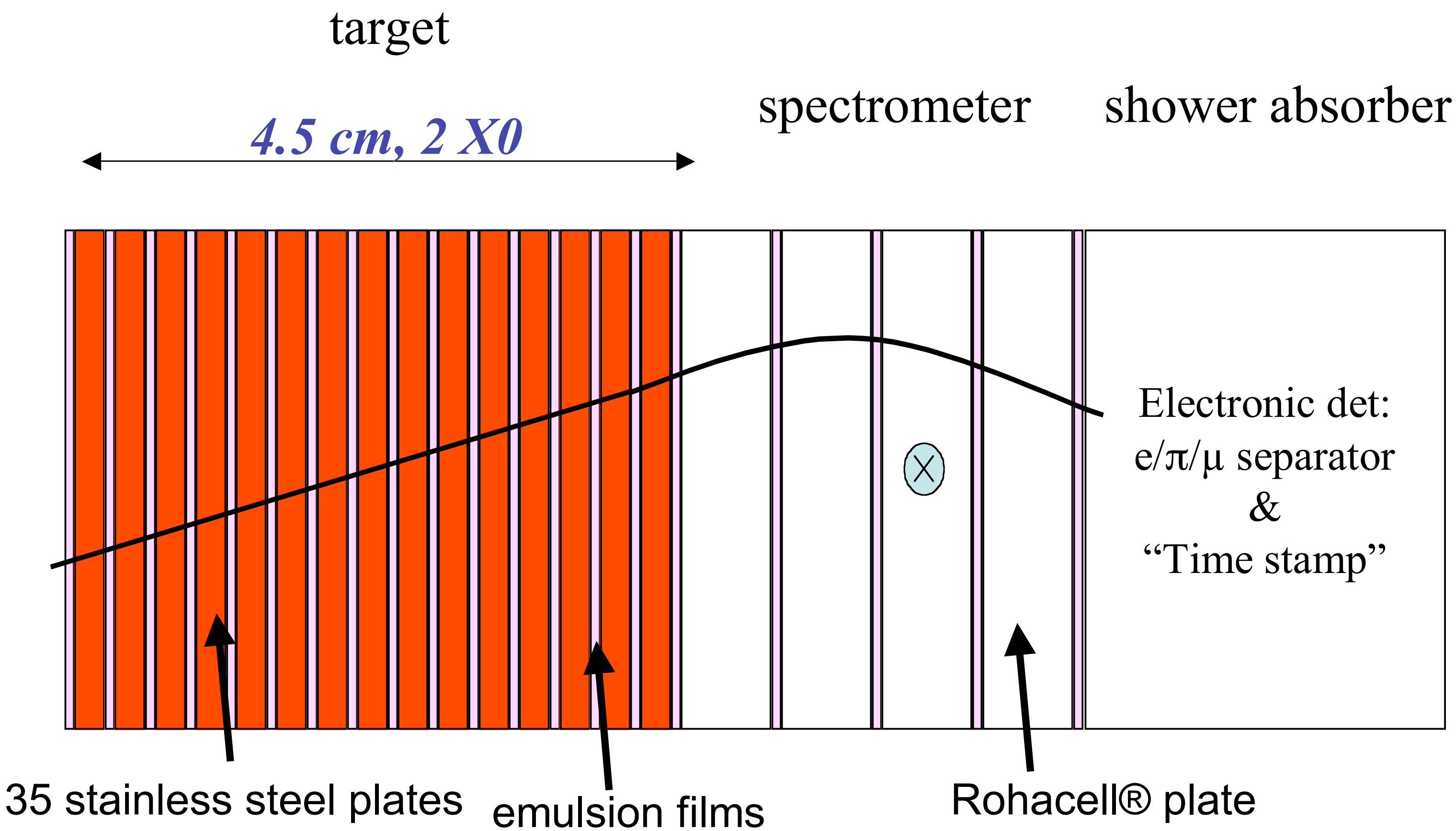
Figure 24: GEANT4 view of the simulated TASD detector.

Similar to MIND … without the iron!

Better muon tracking ability for low momentum – for what baseline is this useful?
To be investigated: sign determination for electrons!

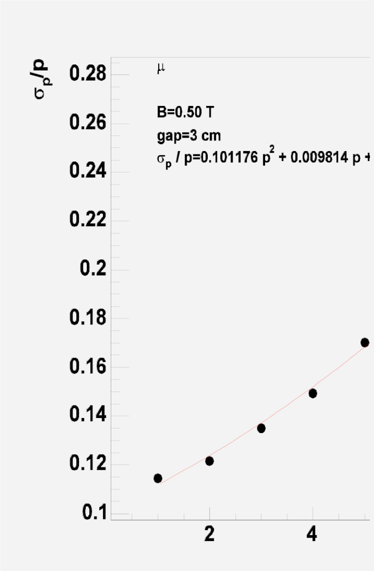
interest in the concept of a lower energy Neutrino Factory
(due to the lower threshold than the baseline magnetised iron detector) but more work is required in order to bring the understanding of this device to a comparable level to the baseline (hadron decays, efficiencies, available mass…)

Magnetized ECC structure



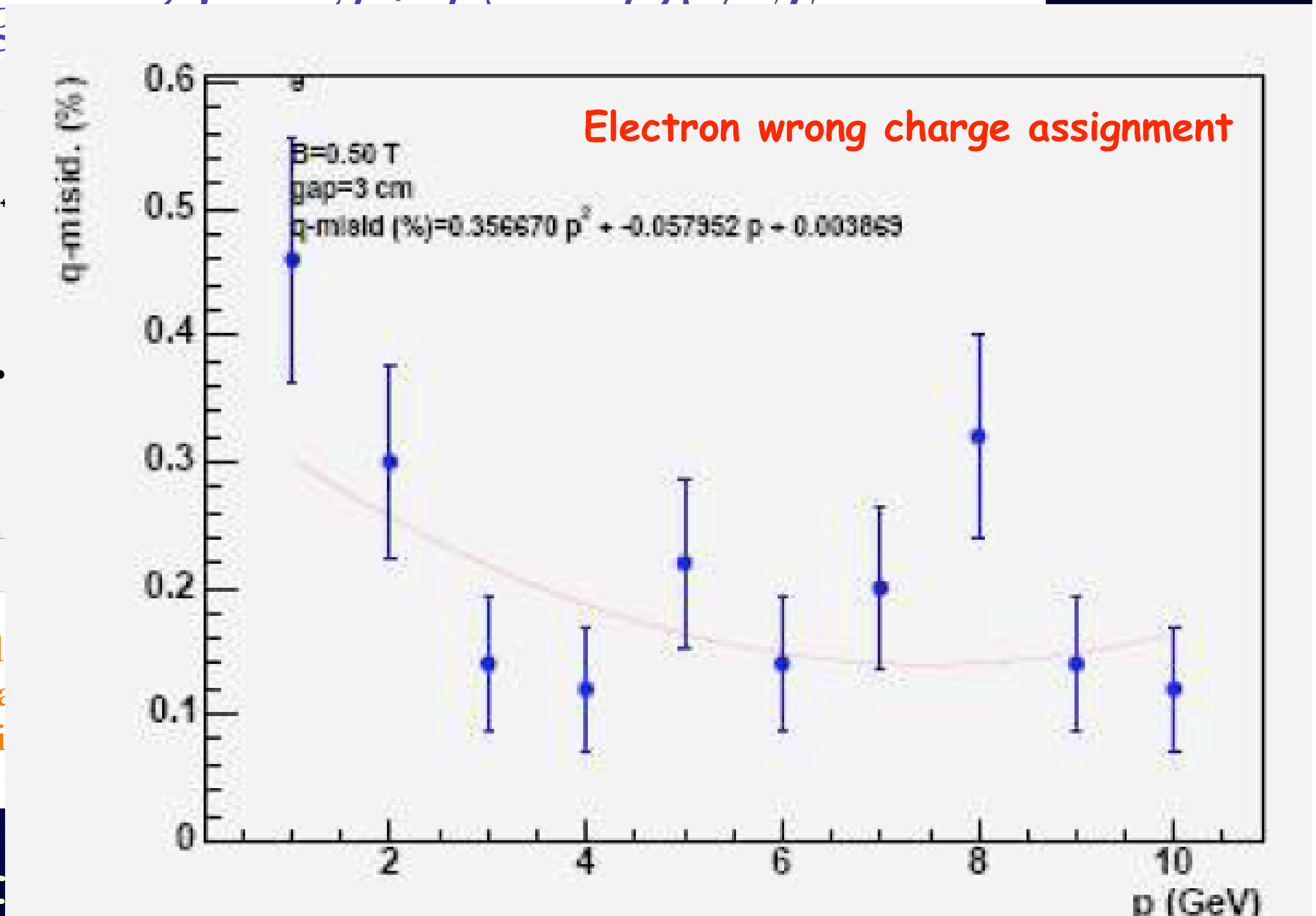
We have focused on the "target + spectrometer" optimization

μ end electron momentum resolution:
3 g



For the electron onl
parabolic fit (Kalma
Given the non negli
downstream for the

FIRST INDICATI



-- Liquid Argon TPC:

DOE (detector of everything)

it can do everything… wether it can do it BETTER than a dedicated standard technique is to be quantitatively demonstrated case by case.

impressive progress from ICARUS T600

recent highlights
-- effort at FERMILAB
-- 2 efforts in EU: ICARUS and GLACIER
-- observation of operation in magnetic field
-- programme on-going to demonstrate long drift, or long wires

talks by Badertscher, Menary, A.Rubbia

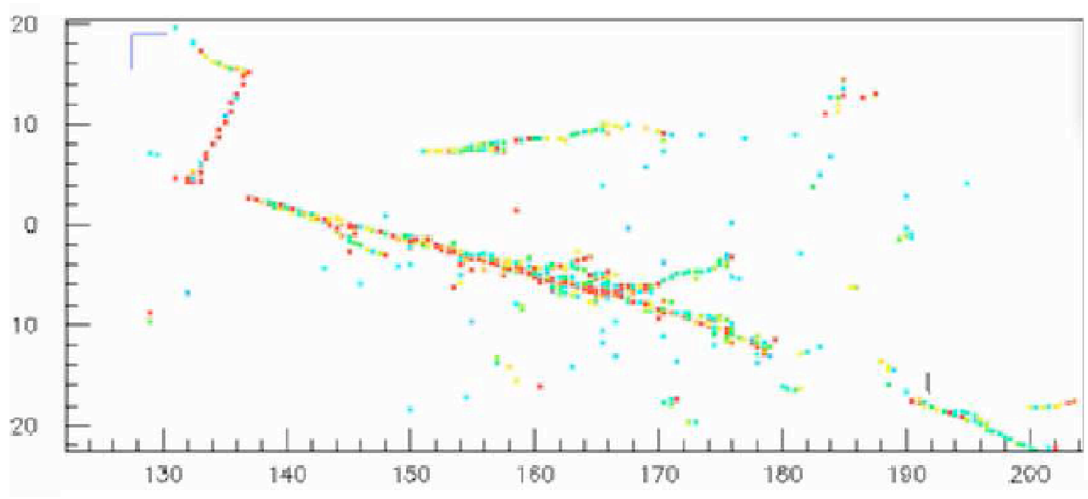
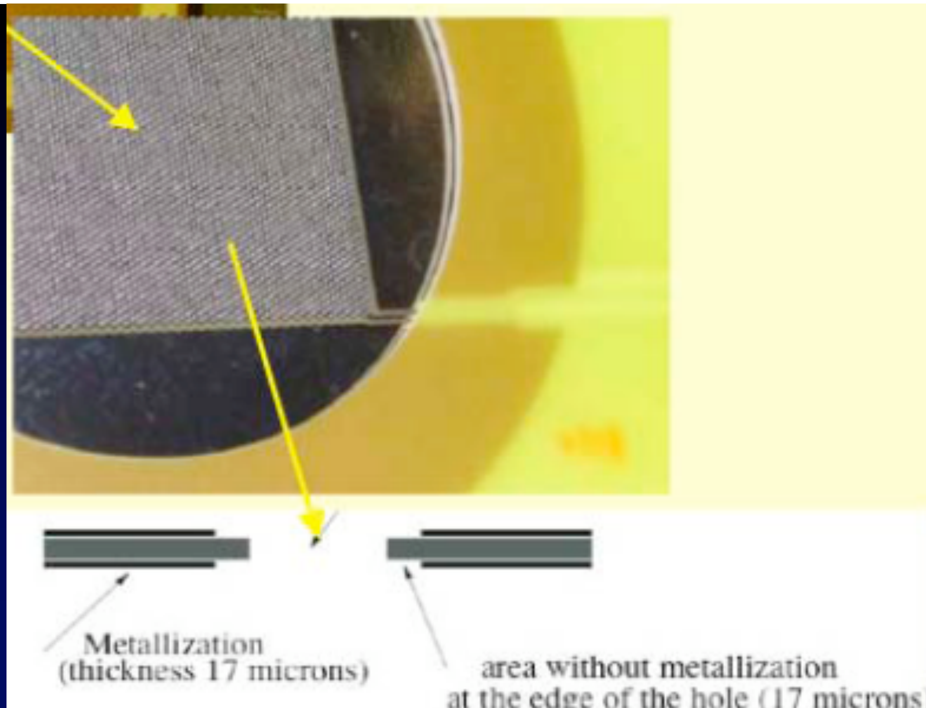
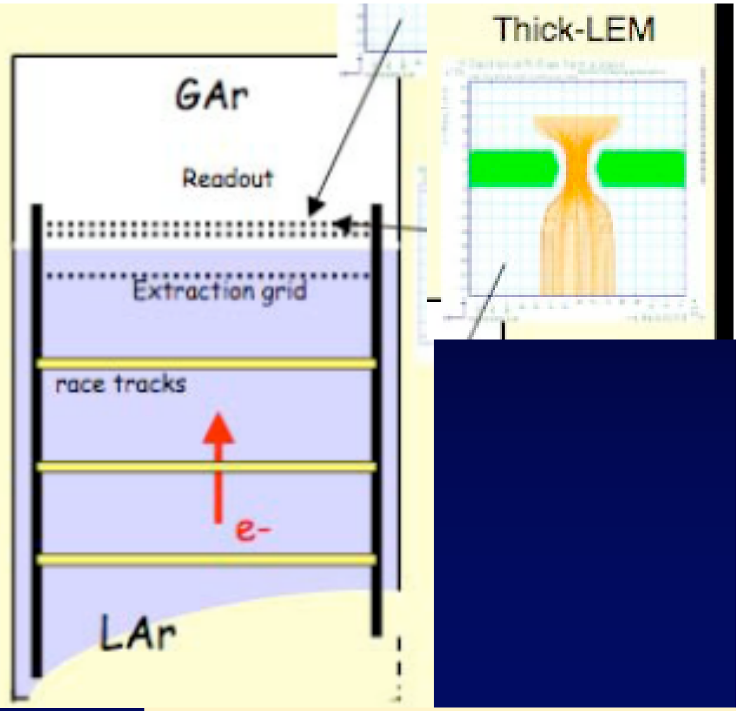
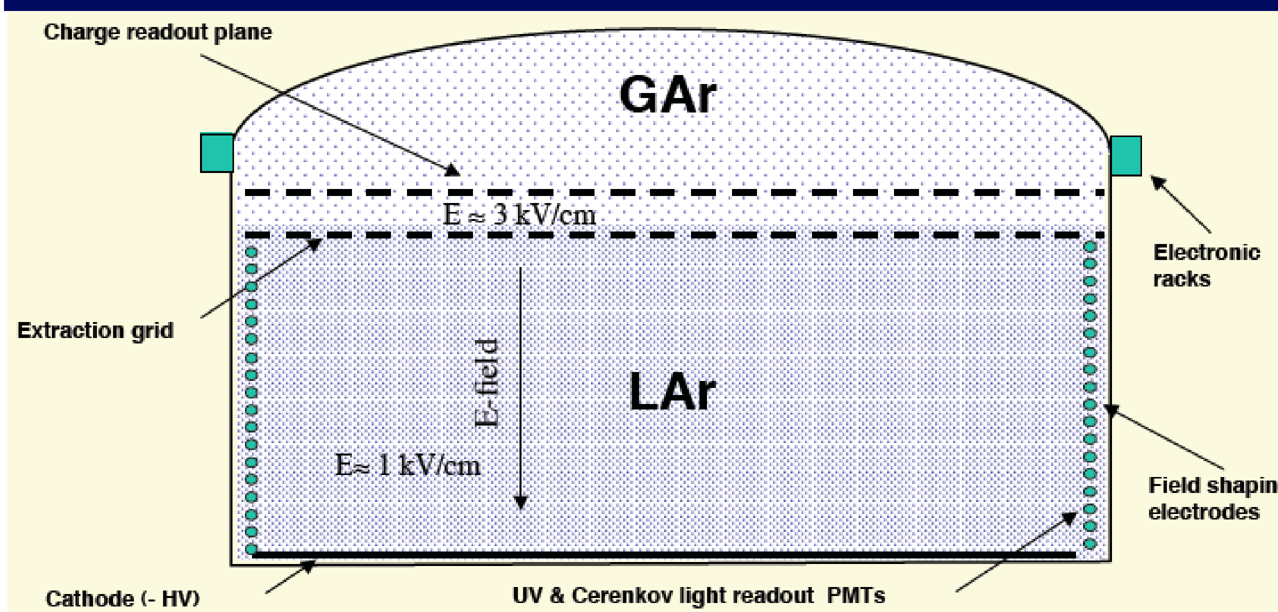


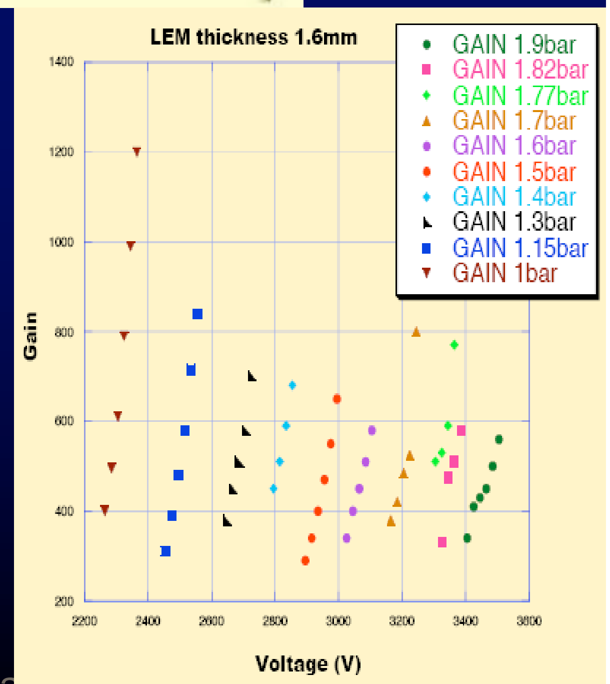
Figure 30: A simulated neutral current event with a 1 GeV π^0 ($\nu_\mu + n \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + n$). Sampling rate is every 3.5% of a radiation length in all three views.





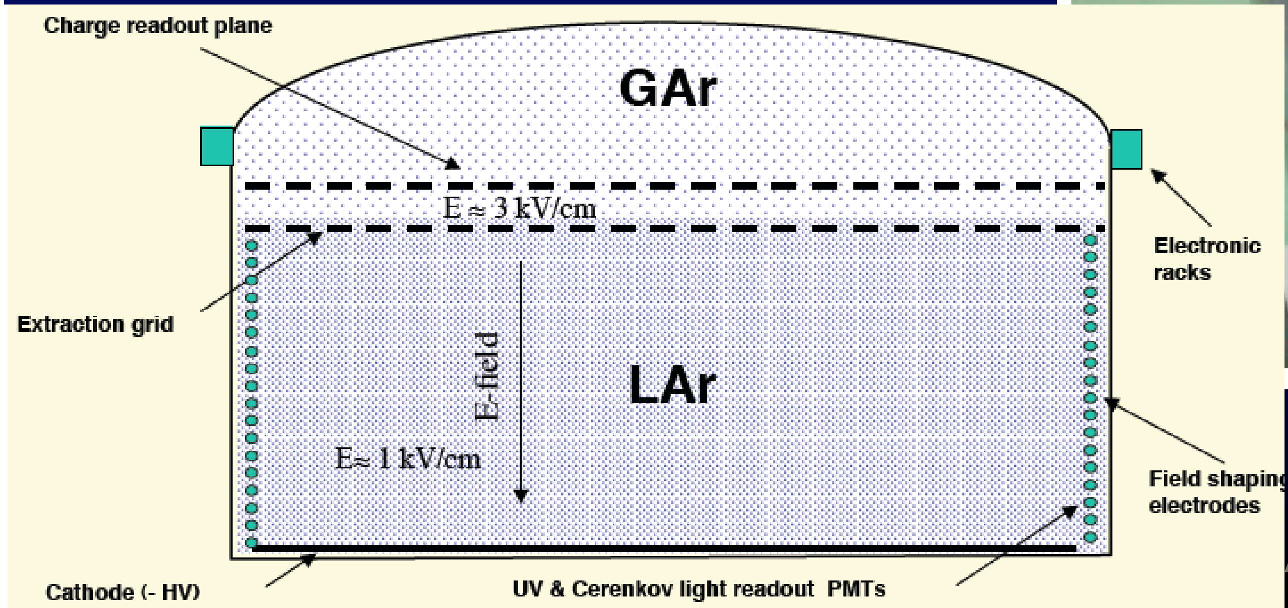
considerable noise reduction can be obtained by gas amplification

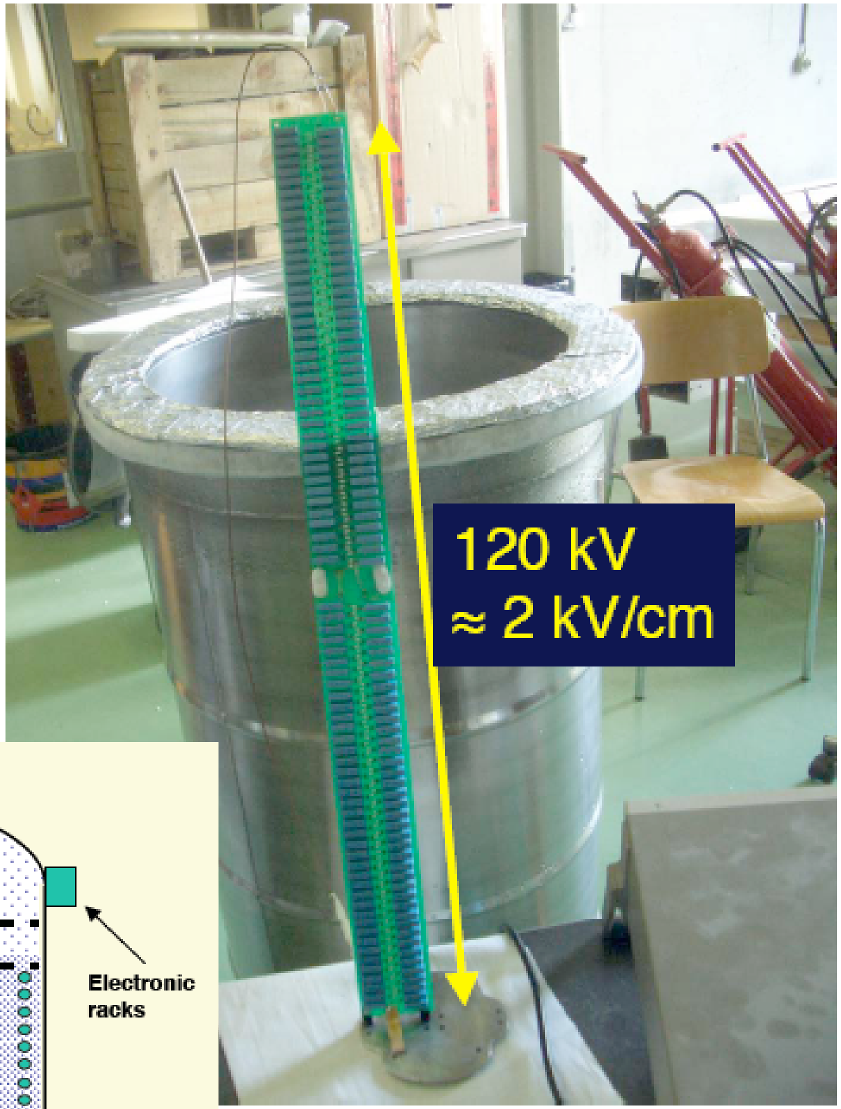




height is limited by high voltage
1kV/cm → 2 MV for 20m…

field degrader in liquid argon tested →
(Cockroft-Greinacher circuit)

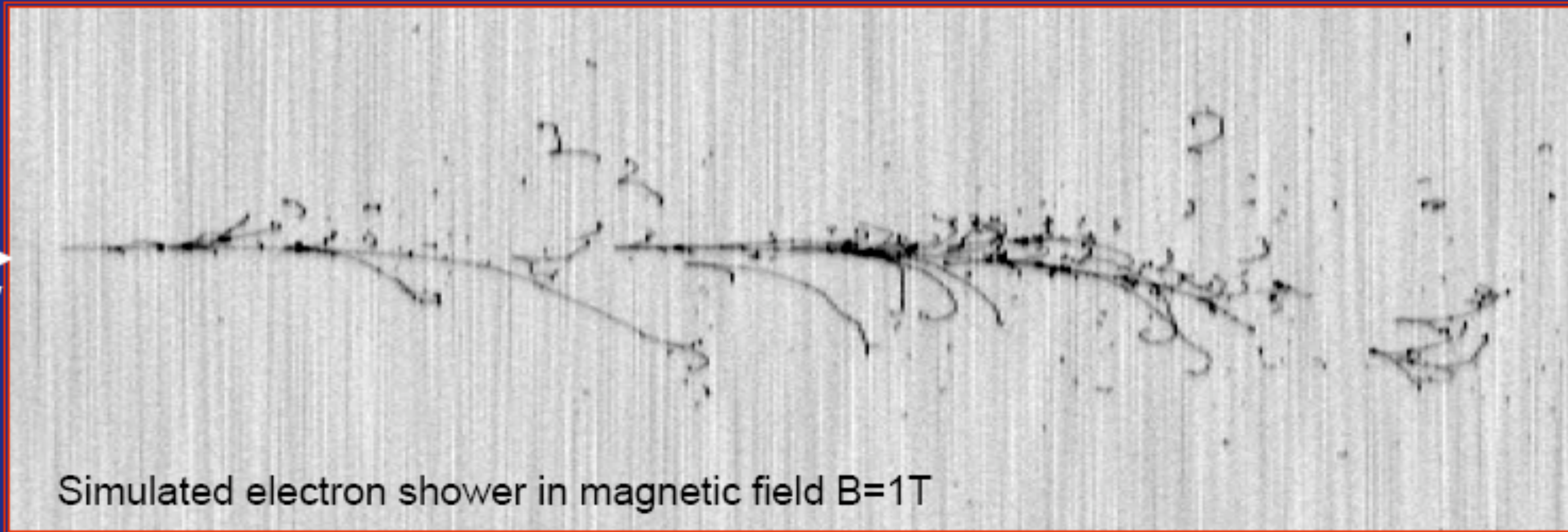




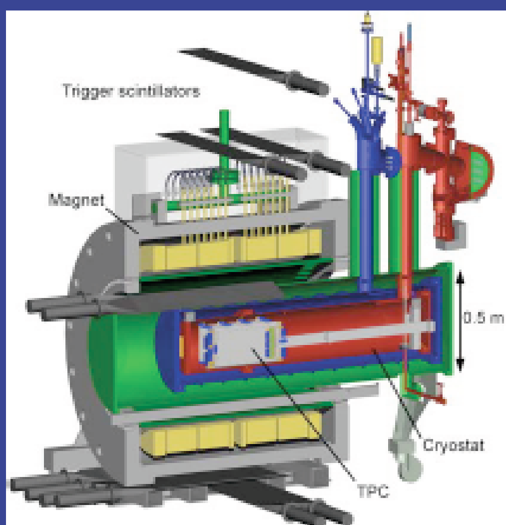
A superconducting magnetized LAr TPC detector

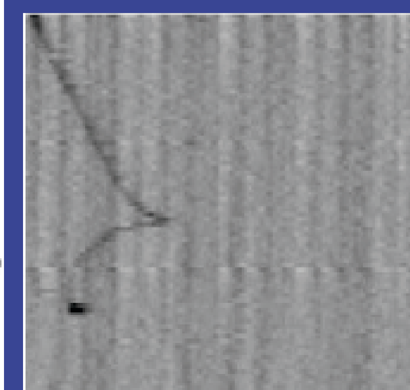
e^-

2.5 GeV



First real events in B-field (B=0.55T):





Required field for 3σ charge discrimination:

x=track length

λ=pitch angle

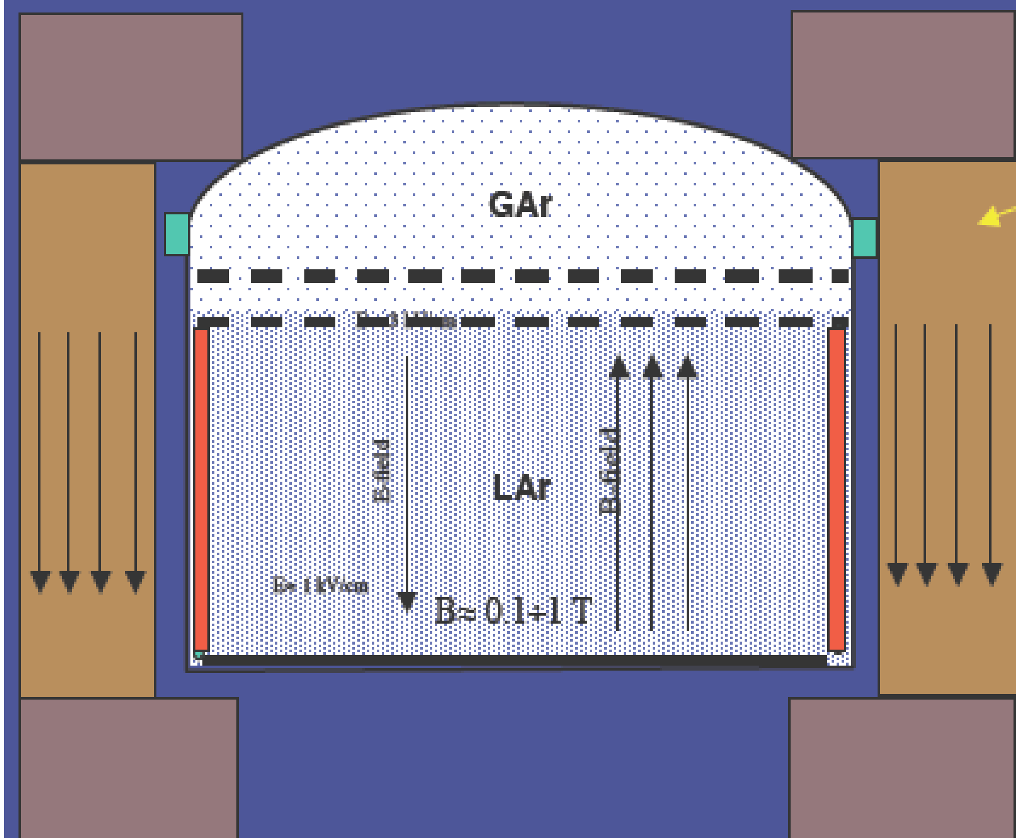
$$B \geq \frac{0.2\,(Tesla)}{\sqrt{x(m)}\,\cos^3\lambda}$$

x ~ a few X_0=14cm….

B > 0.5 T

Tentative Yoke parameters

Cylindrical Fe yoke	10 kton LAr			100 kton LAr		
Magnetic induction (T)	0.1	0.4	1.0	0.1	0.4	1.0
Magnetic flux (Weber)	70	280	710	385	1540	3850
Assumed saturation field in Fe (T)	1.8			1.8		
Thickness (m)	0.4	1.6	3.7	1	3.7	8.7
Height (m)	10			20		
Mass (kton)	6.3	25	63	34	137	342



Cylindrical Fe yoke.
(Instrumented?)

NB: Superconducting Magnetic Energy Storage (SMES) systems were considered for underground storage of MJ energy without return yoke buried in tunnels in bedrock (see e.g. Eyssa and Hilal, J. Phys. D: Appl. Phys 13 (1980) 69). Avoid using a yoke?

SYSTEMATICS - related topics

for NUFACT:

→ work on systematic errors on matter effect

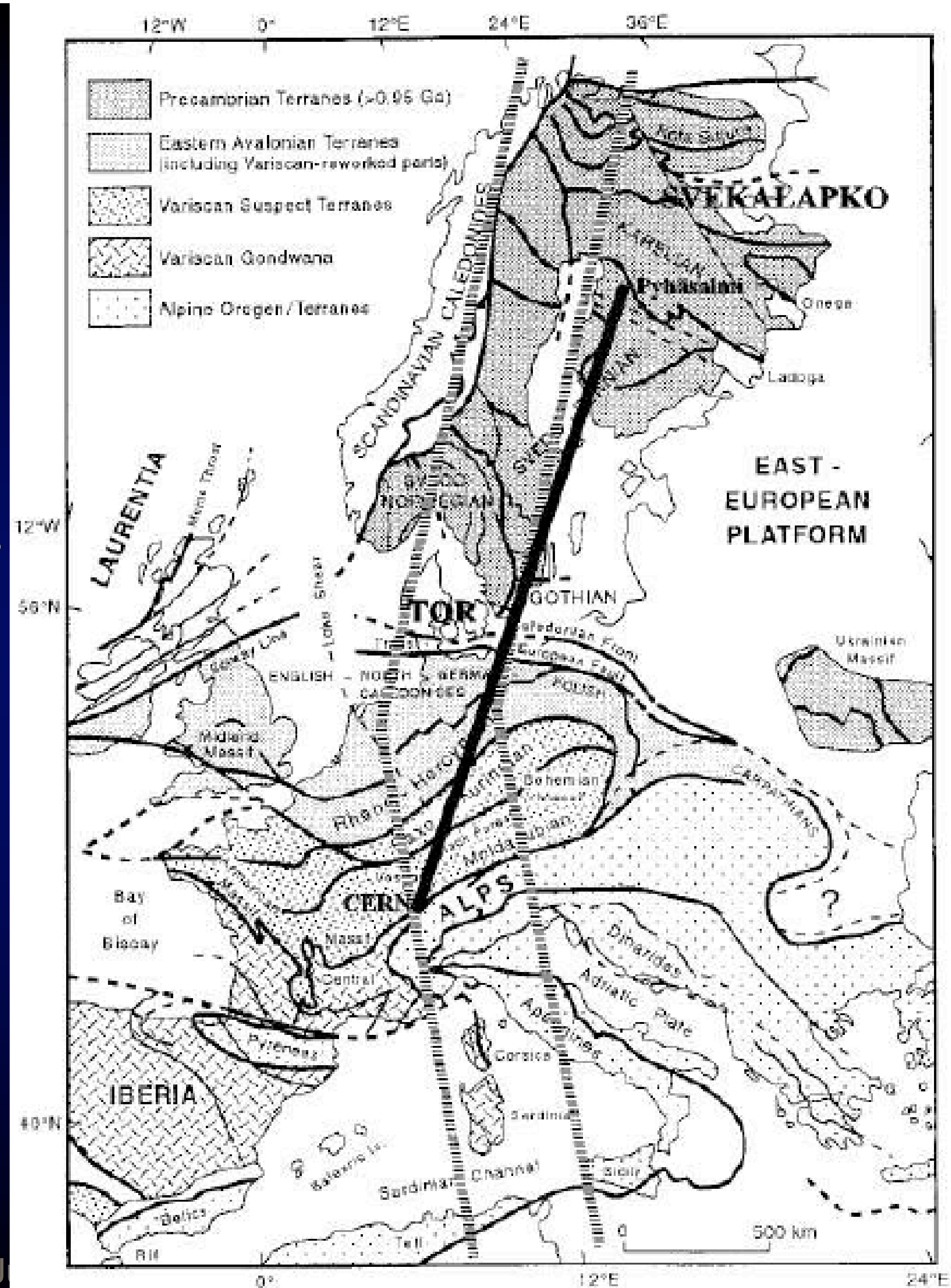
A preliminary study was made by

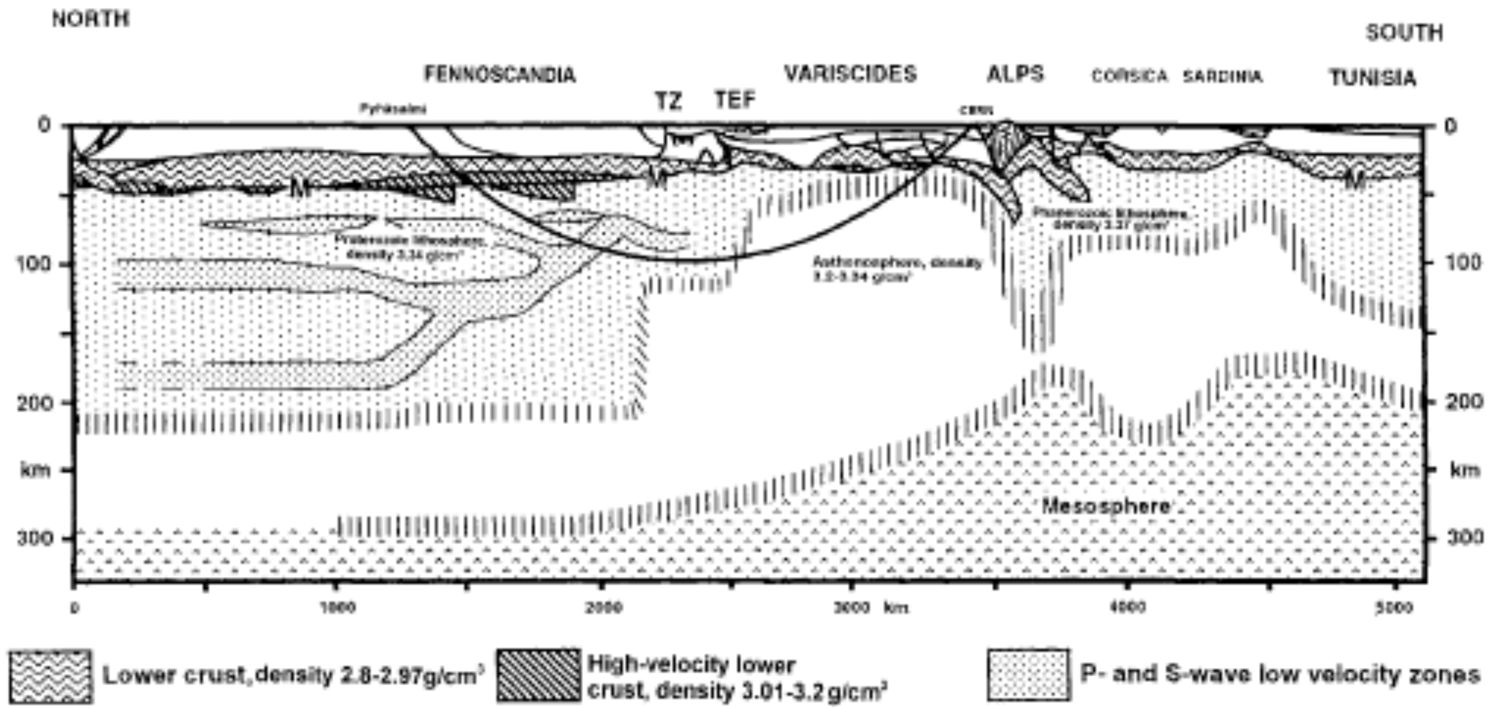
E. Kozlovskaya, J. Peltoniemi, J. Sarkamo,

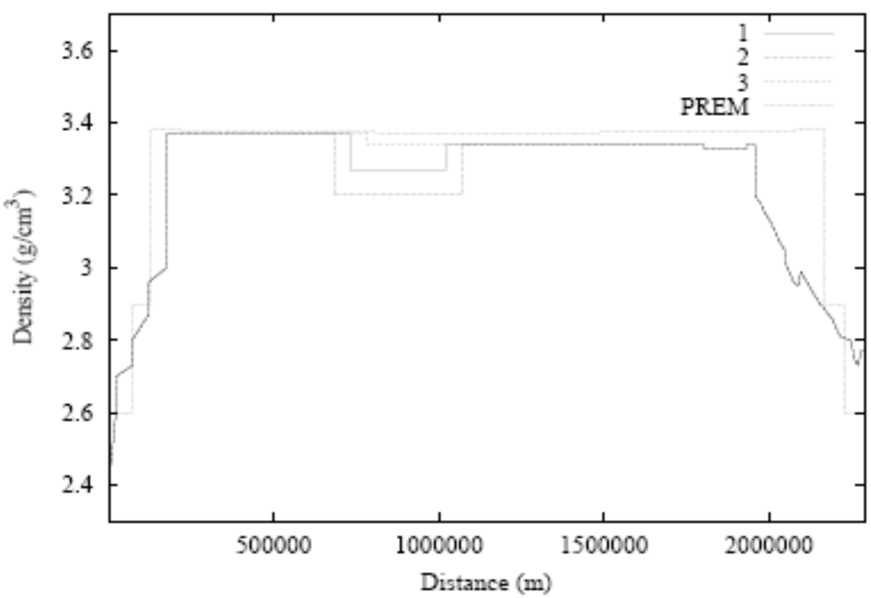
The density distribution in the Earth along the CERN-Pyhäsalmi baseline and its effect on neutrino oscillations. **CUPP-07/2003**

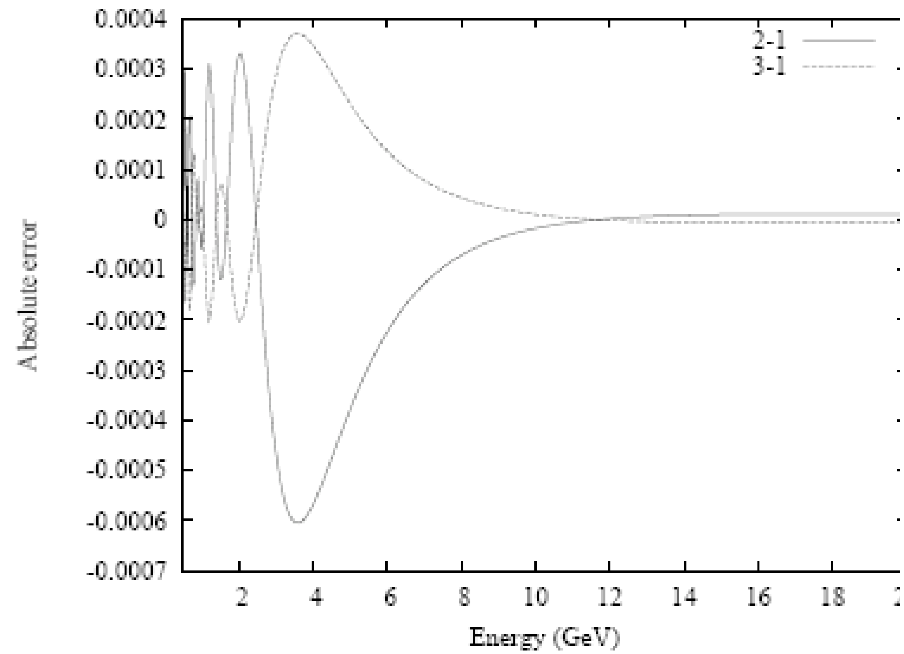
→the uncertainties on matter effects are at the level of one %

J. Peltoniemi




NORTH
SOUTH
FENNOSCANDIA
TZ
TEF
VARISCIDES
ALPS
CORSICA
SARDINIA
TUNISIA
Mesosphere
km
Lower crust, density 2.8-2.97g/cm³
High-velocity lower crust, density 3.01-3.2 g/cm³
P- and S-wave low velocity zones


1
2
3
PREM
Density (g/cm³)
Distance (m)


2-1
3-1
Absolute error
Energy (GeV)

Errors in density

location	length	"a priori"	"best"
Continental	2500 km	4.7%	2.9%
Oceanic	2500 km	2.6%	1.7%
Continental	9000 km	2.0%	1.7%
Oceanic	9000 km	1.8%	1.5%

Errors are ~2 sigma
(but not really Gaussian)

Avoid perturbed terrain (europe or US to Japan, across the alps, etc…)
Dedicated study would reduce errors to below 2%
→ 2% is standard hypothesis for Nufact studies

Near detectors and flux instrumentation

Near detector constraints for CP violation

ex. beta-beam or nufact:

$$\frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} = A_{CP} \ \alpha \ \frac{\sin\delta \sin(\Delta m^2_{12} L/4E) \sin\theta_{12} \sin\theta_{13}}{\sin^2\theta_{13} + \text{solar term...}}$$

Near detector gives ν_e diff. cross-section*detection-eff *flux and ibid for bkg

BUT: need to know ν_μ and $\bar{\nu}_\mu$ diff. cross-section* detection-eff

with small (relative) systematic errors.

→knowledge of cross-sections (relative to each-other) required

→knowledge of flux!

interchange role of ν_e and ν_μ for superbeam experimental signal= signal cross-section X efficiency of selection + Background

$$\sigma_{sig} = \sigma \times \varepsilon + B$$

need to know this:

$$\frac{\sigma^{\nu_e}_{sig} / \sigma^{\nu_\mu}_{sig}}{\sigma^{\bar{\nu}_e}_{sig} / \sigma^{\bar{\nu}_\mu}_{sig}}$$

this is not a totally trivial quantity as there is somethig particular in each of these cross-sections:

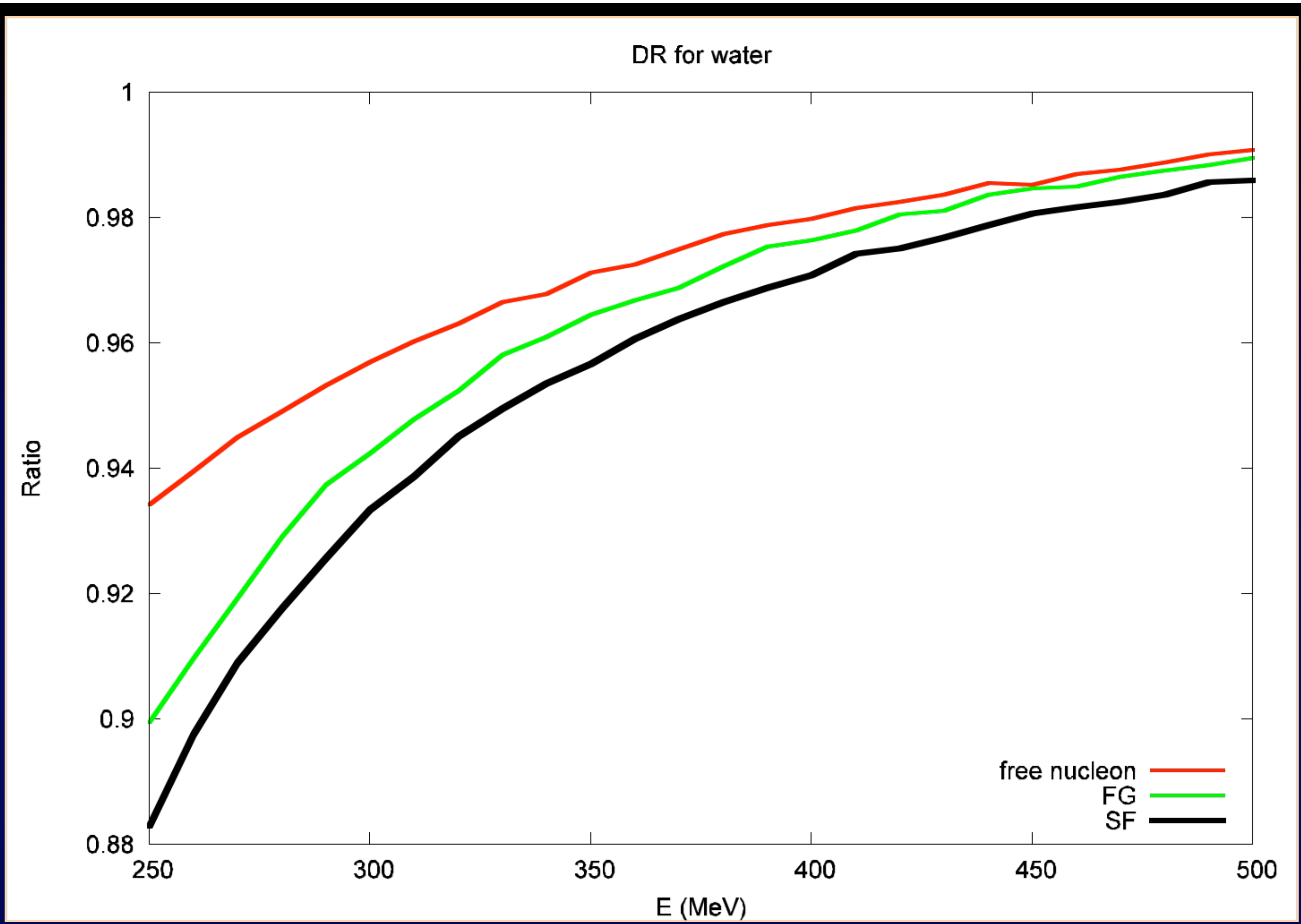
for instance the effects of muon mass as well as nuclear effects are different for neutrinos and anti-neutrinos

while e.g. pion threshold is different for muon and electron neutrinos

and of course the fluxes... but the product flux*σ_{sig} is measured in the near detector

$$DR \equiv \frac{\dfrac{\sigma(\nu_\mu)}{\sigma(\nu_e)}}{\dfrac{\sigma(\bar{\nu}_\mu)}{\sigma(\bar{\nu}_e)}}$$

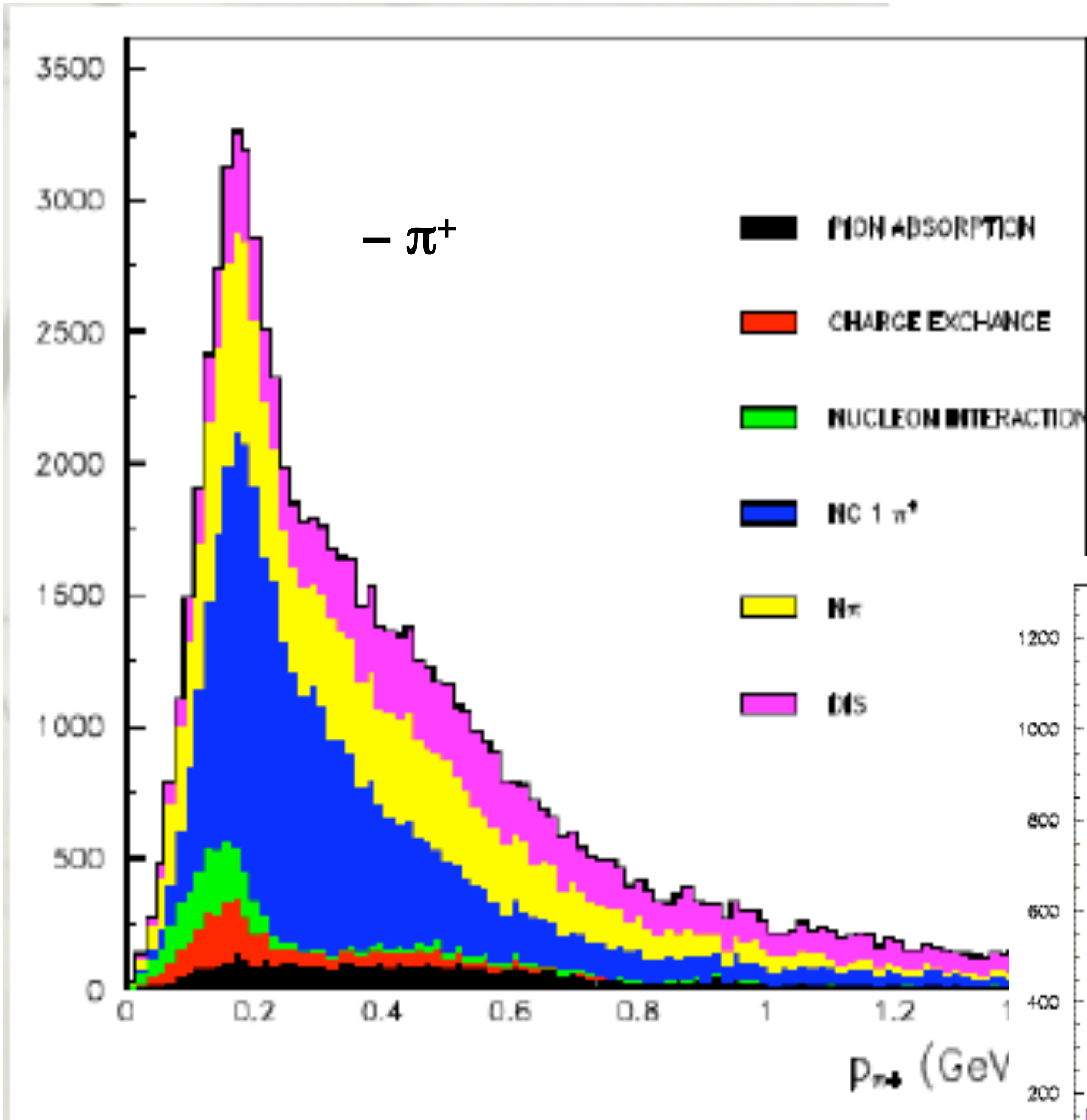
for WATER:
(free protons
+ Oxygen)

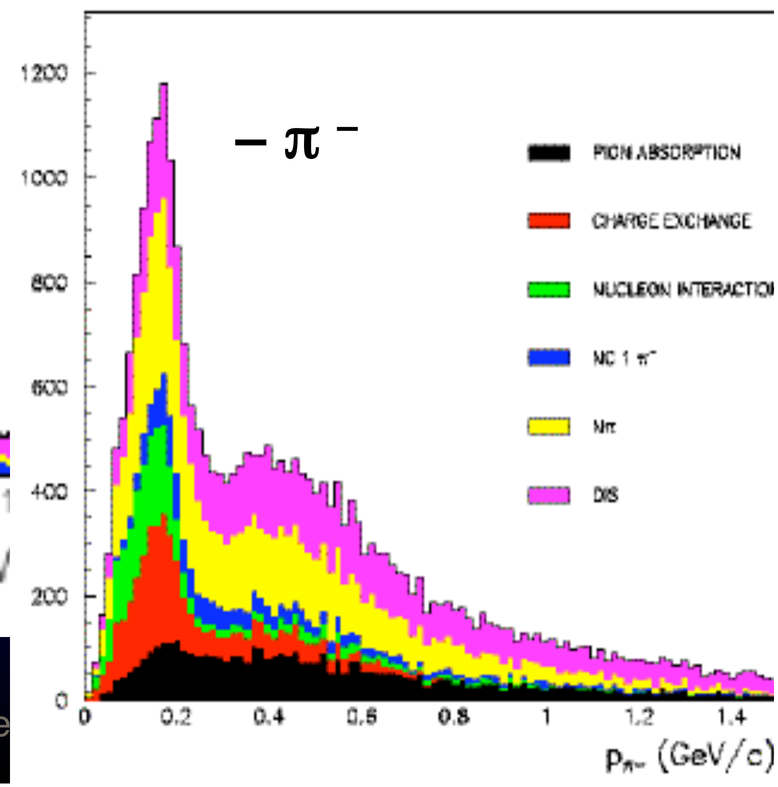


at 250 MeV (first maximum in Frejus expt) prediction varies from 0.88 to 0.94 according to nuclear model used.
(but what systematic error does one assign to this.?)

Nuclear reinteractions

Single track events….
(single ring in Water Cherenkov…)





FLUX in NUFACT will be known to 10^{-3}

this was studied including

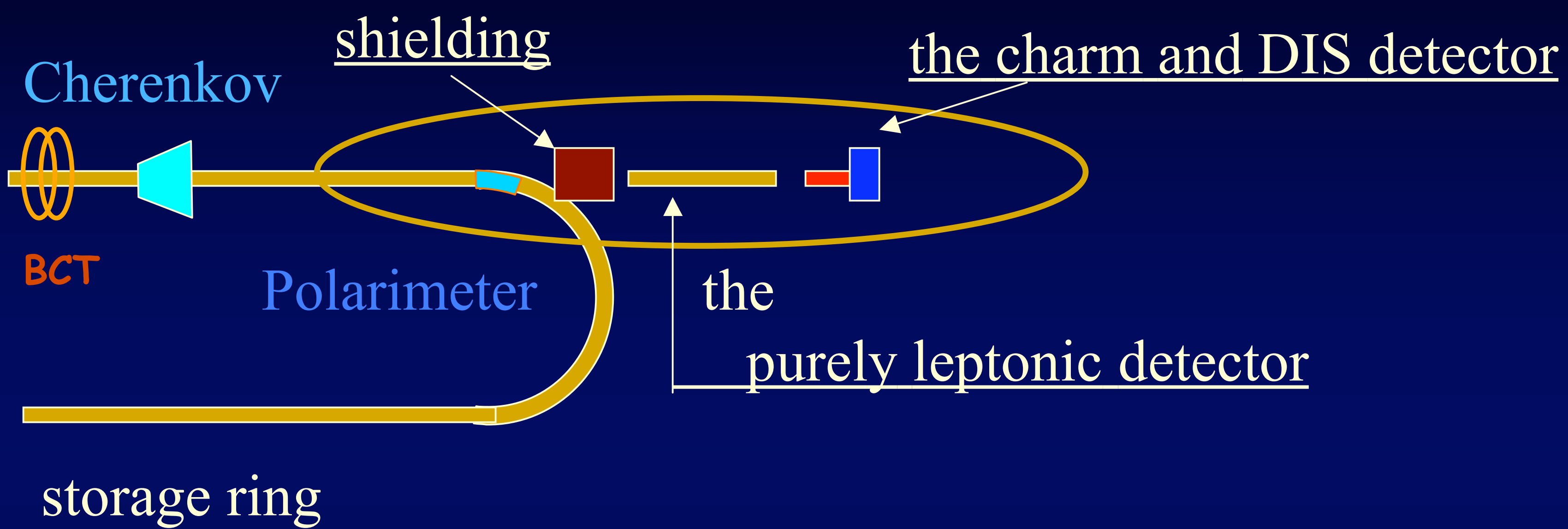
-- principle design of polarimeter, and absolute energy calibration
-- principle design of angular divergence measurement <-- to revisit
-- radiative corrections to muon decay
-- absolute x-section calibration using neutrino – electron interactions
(event number etc… considered)

ν_e

this is true for

ν_e $\bar{\nu}_\mu$

$\bar{\nu}_e$ ν_μ



from the precision of this sketch, it can be concluded that a lot remains to be done.

for instance:

→is shielding necessary at all?

→Is the Cherenkov feasible; for muons? for ions (beta-beam)?

Muon Polarization

muons are born longitudinally polarized in pion decay (~18%)
depolarization is small (Fernow &Gallardo)

effects in electric and magnetic fields is (mostly) described by spin tune:

$$\nu = a_\mu \gamma = \frac{g_\mu - 2}{2} \frac{\mathrm{E_{beam}}}{m_\mu} = \frac{\mathrm{E_{beam}(GeV)}}{90.6223(6)}$$

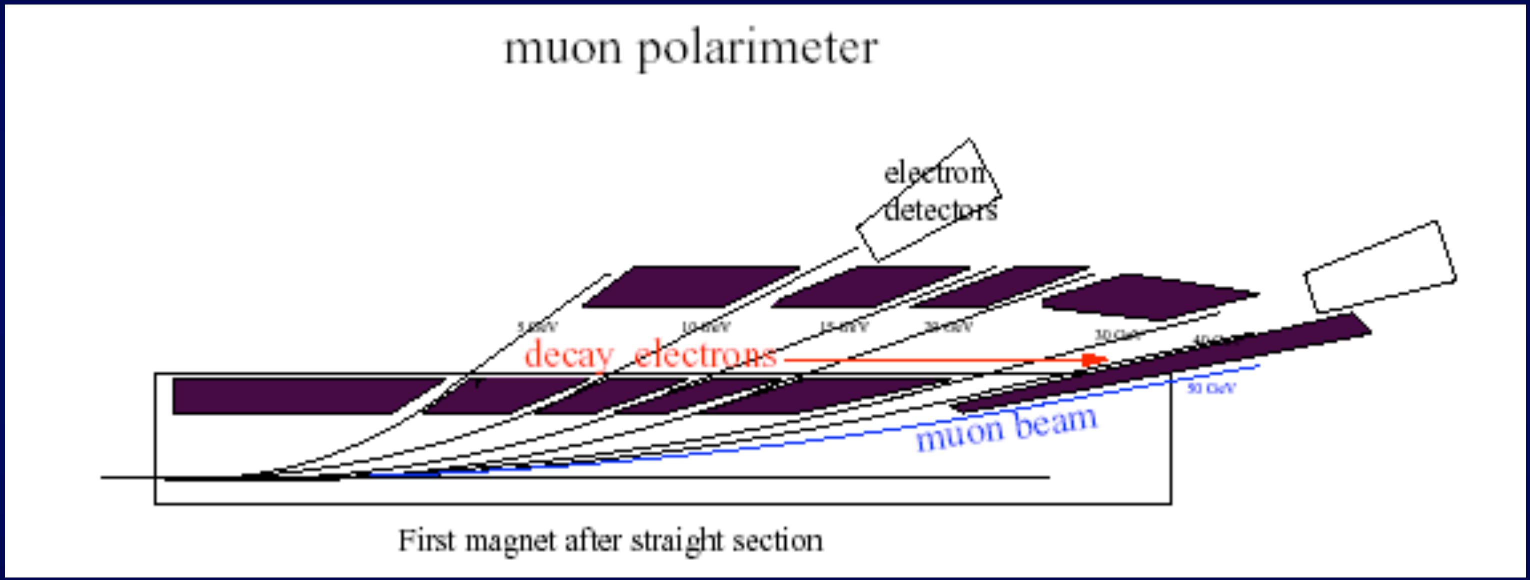
which is small: at each kick θ of a 200 MeV/c muon the polarization is kicked by $\nu.\theta = 0.002\ \theta$

in the high energy storage ring polarization precesses. Interestingly $\nu = 0.5$ for a beam energy of 45.3112 GeV: at that energy it flips at each turn.

Muon Polarization

muon polarization is too small to be very useful for physics (AB, Campanelli) but it must be monitored.

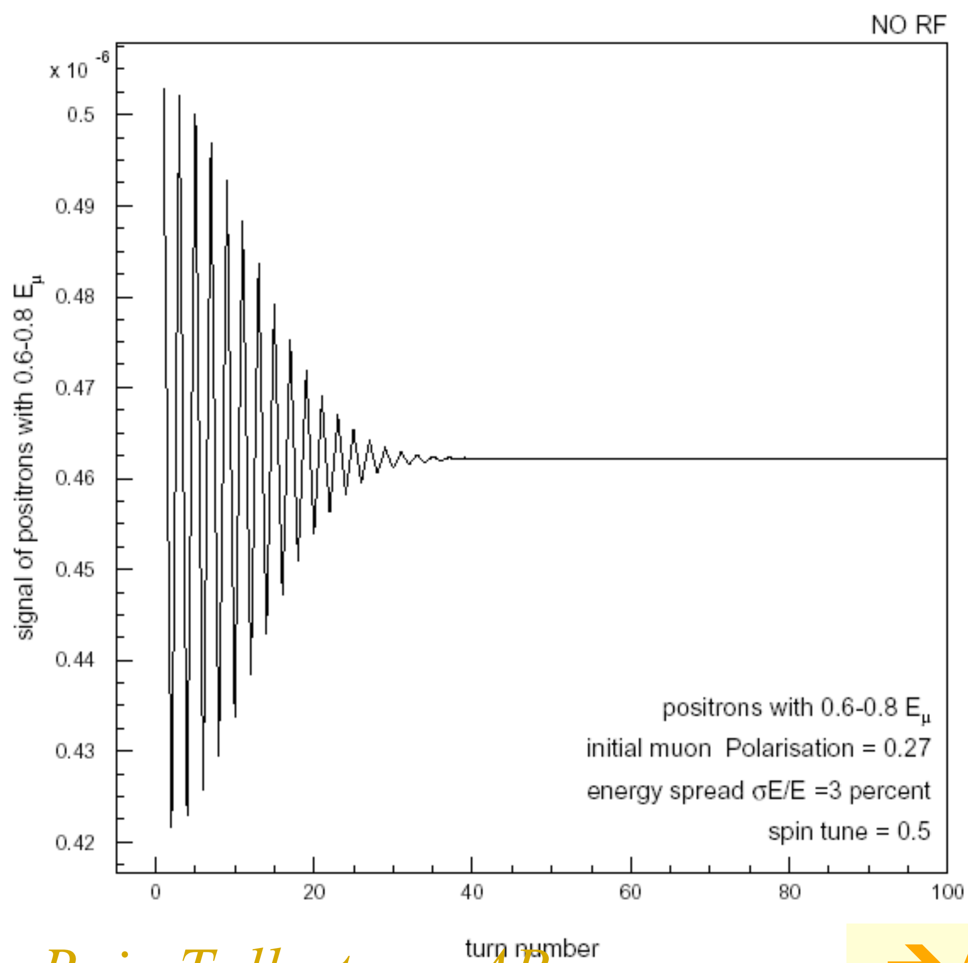
In addition it is precious for energy calibration (Raja&Tollestrup, AB)



a muon polarimeter would perform the momentum analysis of the decay electrons at the end of a straight section.

Because of parity violation in muon decay the ratio of high energy to low energy electrons is a good polarization monitor.

muon polarization



here is the ratio of
positons with E in [0.6-0.8] E_μ
to number of muons in the ring.
← There is no RF in the ring.

spin precession and
depolarization are clearly visible
This is the Fourier Transform
of the muon energy spectrum
(AB)
amplitude=> polarization
frequency => energy
decay => energy spread.

Raja Tollestrup, AB

➔ $\Delta E/E$ and $\sigma E/E$ to 10^{-6}
➔ polarization to a few percent.

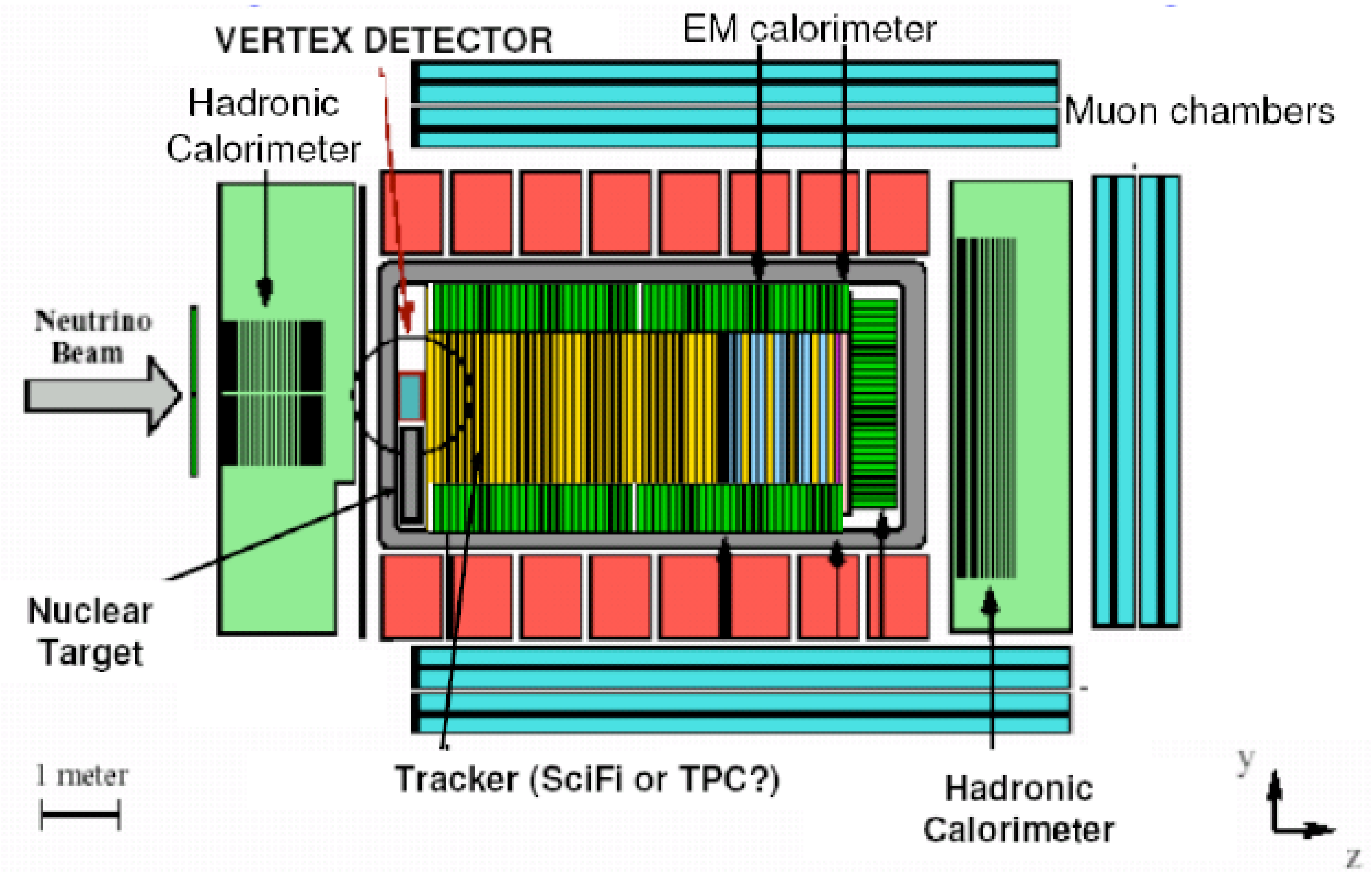


Figure 13: *Possible geometry for a near detector at a neutrino factory.*

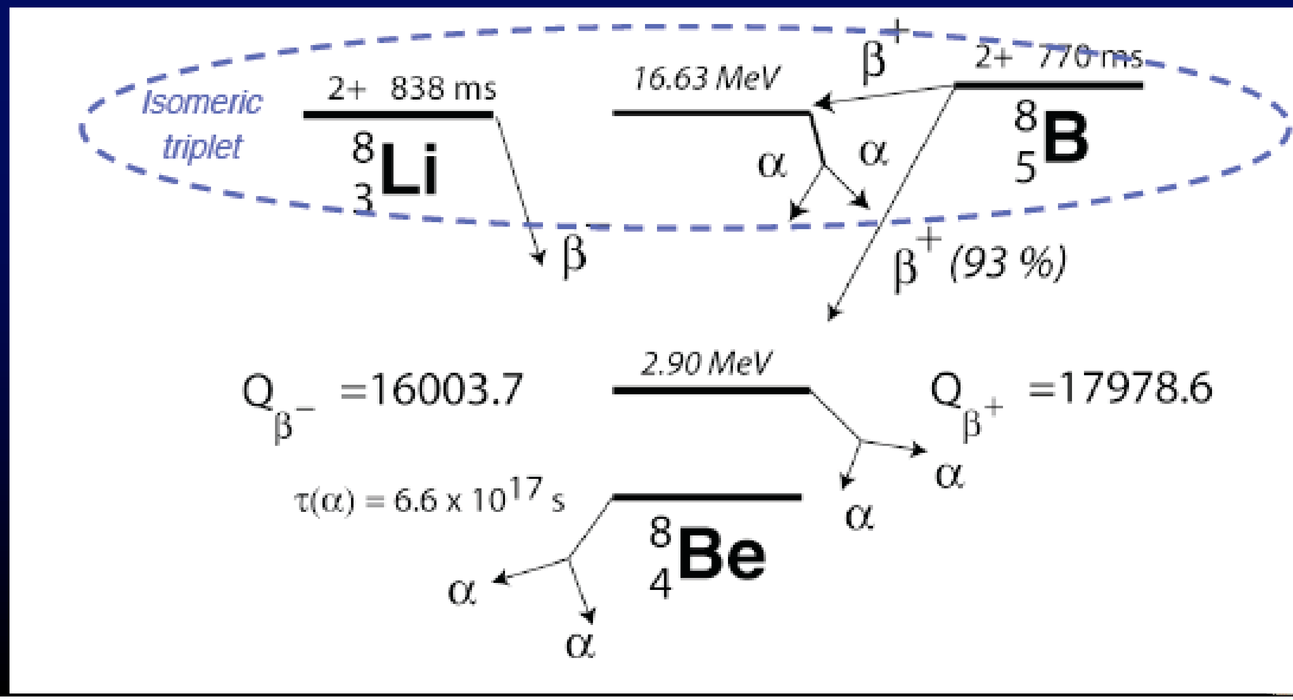
Better beta beams

main weakness of He/He beta-beam is low energy
(450 GeV proton equiv. storage ring produces 600 MeV neutrinos)

Solution 1: Higher γ (Hernandez et al)
Use SPS+ (1 TeV) or tevatron ==> reach γ= 350 expensive!

Solution 2: use higher Q isotopes (C.Rubbia)

$^{8}B \rightarrow {}^{8}Be\, e^{+}\, \nu_{e}$
or
$^{8}Li \rightarrow {}^{8}Be\, e^{-}\, \overline{\nu}_{e}$



A possible solution to the ion production shortage:

Direct production in a small storage ring,
filled [Gas + RF cavity] for ionization cooling

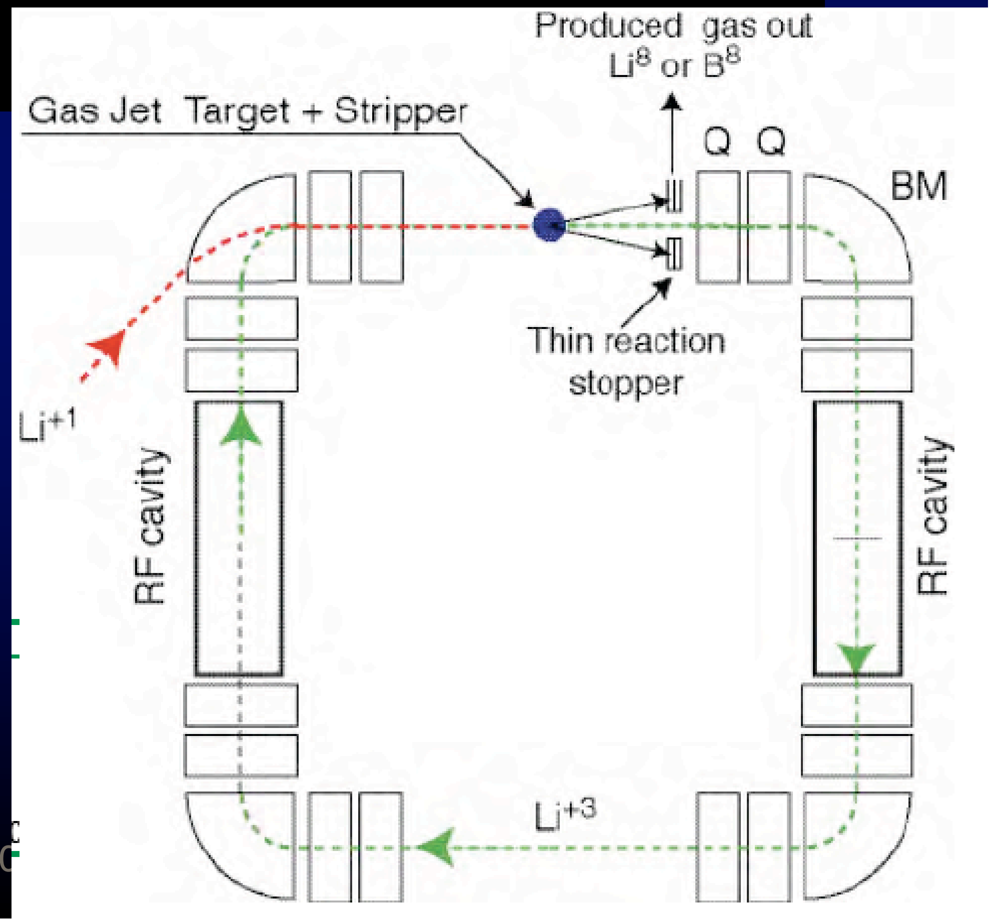
For ^8B or ^8Li production, strip-inject ^6Li / ^7Li beam,
collide with gas jet
(D_2 or ^3He)

$$Li^7 + d \rightarrow Li^8 + p$$

$$Li^6 + He^3 \rightarrow B^8 + n$$

reaction products are
ejected and collected

goal: >~ 10^{21} ions per year



Advantages of $^8B^{5+}$ (ν_e Q=18MeV) or $^8Li^{3+}$ (anti-ν_e Q=16MeV) vs ^{18}Ne, ^6He (Q~=3 MeV)

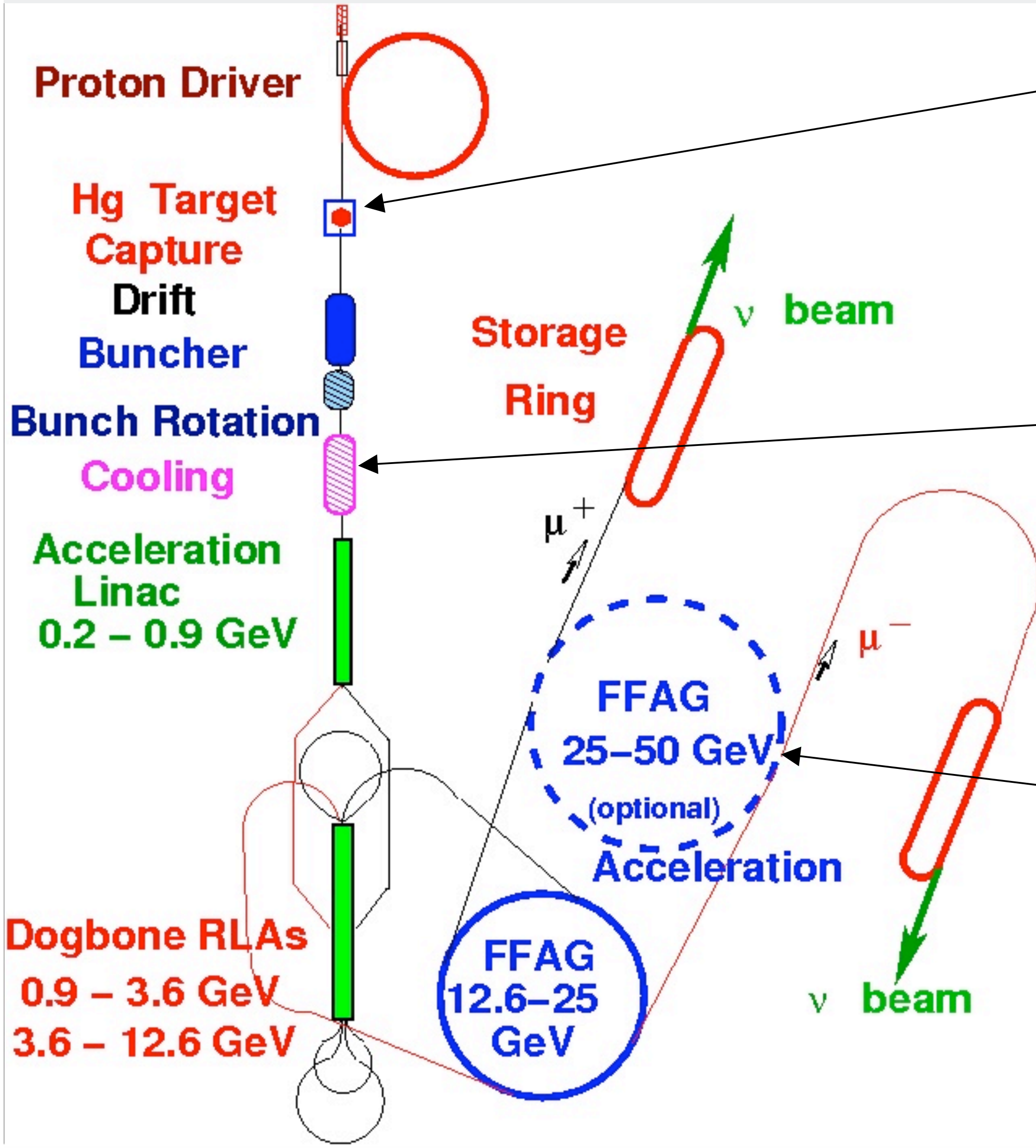
The storage ring rigidity is considerably lower for a given E_ν
==> for ~1 GeV end point beam
for $^8B^{5+}$: 45 GeV proton equiv. storage ring
for $^8Li^{3+}$: 75 GeV proton equiv. storage ring

Two ways to see it:
1. Beta-beams to Fréjus (E_{max} =600 MeV) could be accelerated with PS2 into a 50 GeV proton-equivalent storage ring (save €)
2. Beta beams of both polarities up to end-point energy of ~6 GeV can be produced with the CERN SPS (up to 2000km baseline)

Difficulty: increase of intensity necessary to keep same flux(Q^2) or events (Q) may lead to serious irradiation poblem.

A new flurry of opportunities

Major challenges tackled by R&D expts



High-power target
. 4MW
. good transmission
MERIT experiment (CERN)

Fast muon cooling
MICE experiment (RAL)

Fast, large aperture accelerator (FFAG)
EMMA (Daresbury)

ISS baseline

High intensity proton accelerators pose many challenges but certainly one of the most critical one is the

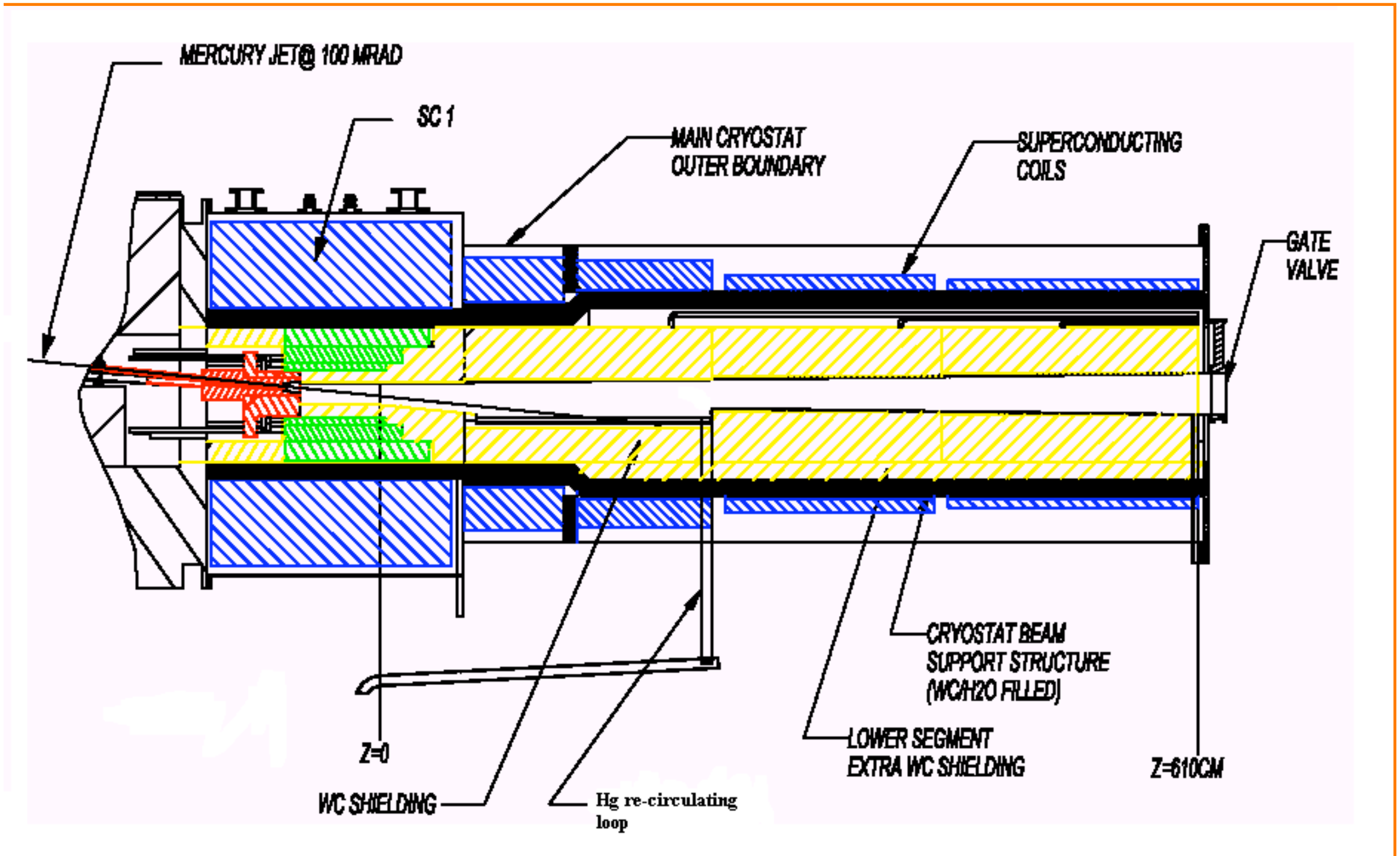
Target !

Typical Dimensions: L $\approx$ 30 cm, R $\approx$ 1 cm

→ 4 MW of protons (i.e. 40 000 light bulbs!) into a big cigar….

it would immediately go to smoke.

Neutrino Factory Study2a Target



The Field Taper

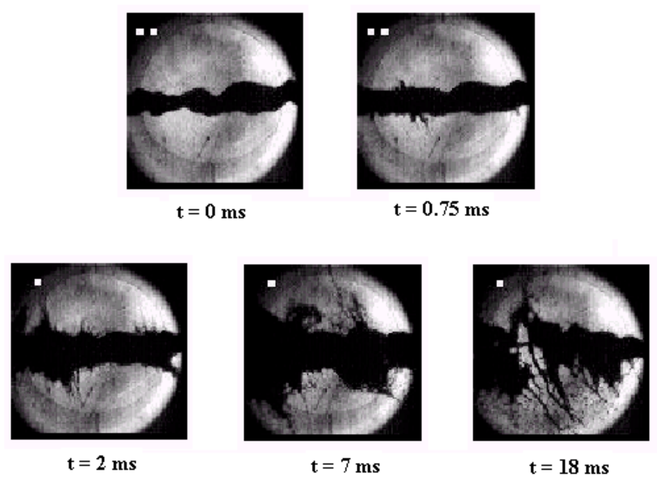
At Z=0m
Bz =20T
Bore = 15cm

At Z=20m
Bz =1.75T
Bore =60cm

Target: Hg jet tests

E951

•1 cm
•v=2.5 cm/s
•24 GeV 4 TP p beam
•No B field

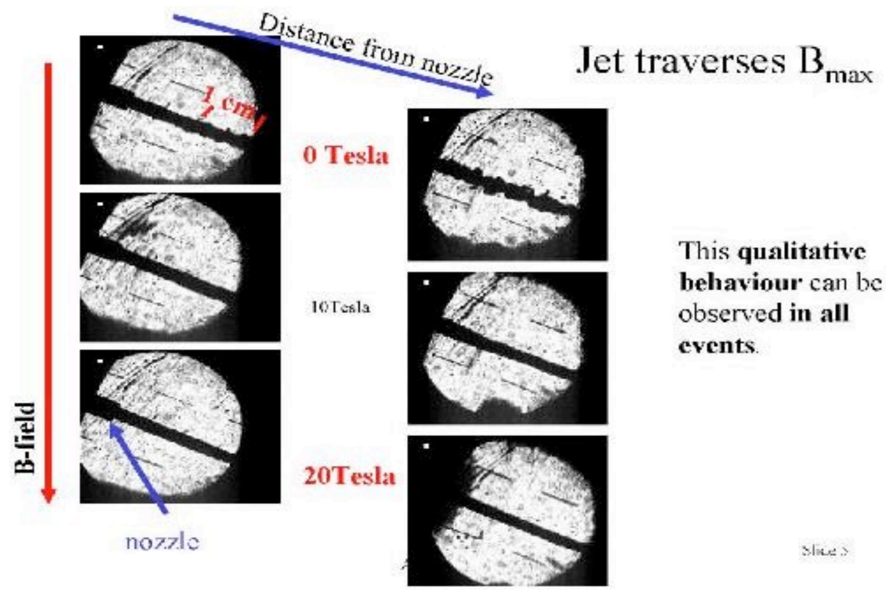


Hg jet dispersal properties :

- proportional to beam intensity
- velocities ~½ times that of "confined thimble" target
- largely transverse to the jet axis
- delayed 40 ms

CERN/Grenoble

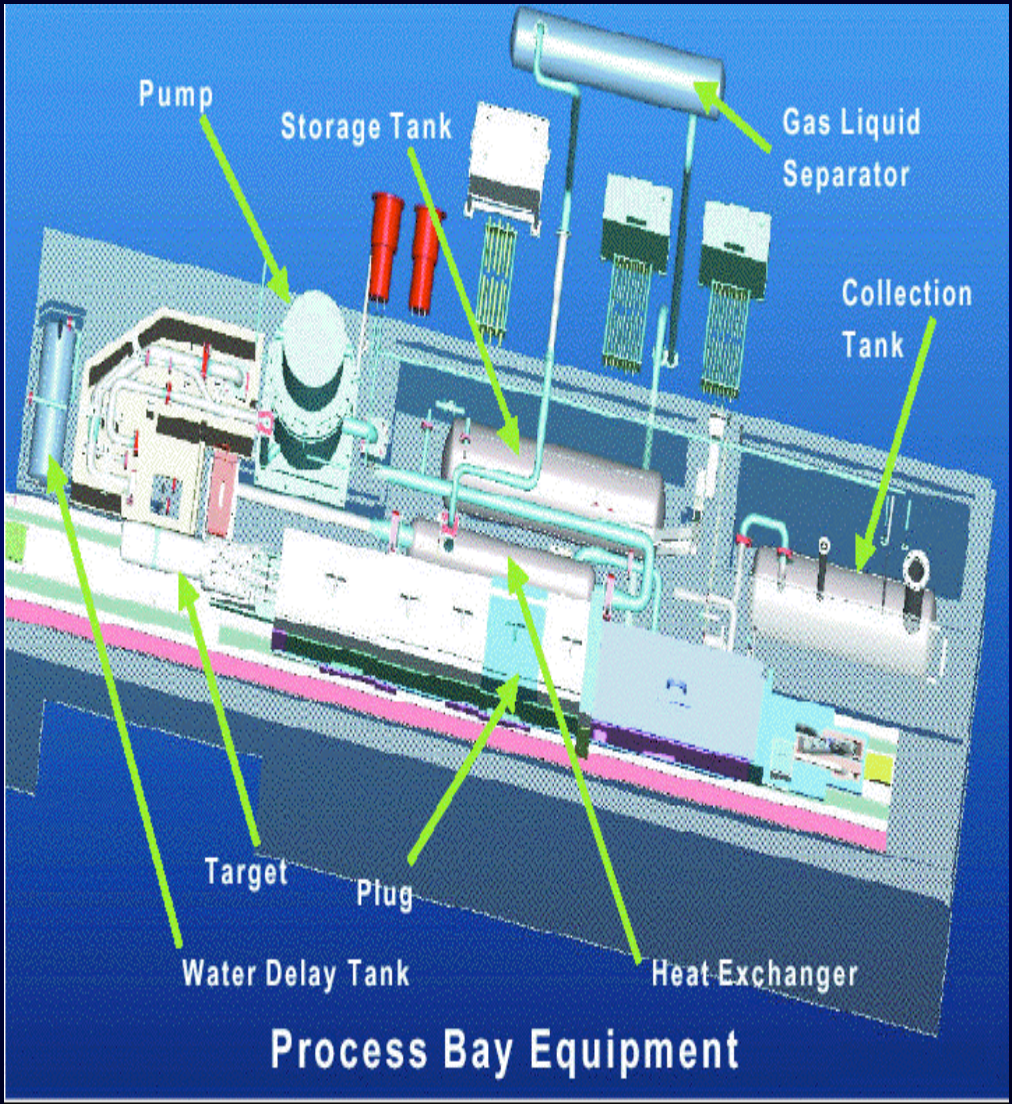
•4 mm
•v=12 m/s
•No p beam
•0,10,20T B field



- The Hg jet is stabilized by the 20 T B field
- Minimal jet deflection for 100 mrad angle of entry
- Jet velocity reduced upon entry to B field

Hg-jet system

Power absorbed in Hg-jet	1 MW
Operating pressure	100 Bar
Flow rate	2 t/m
Jet speed	30 m/s
Jet diameter	10 mm
Temperature	
- Inlet to target 30° C	
- Exit from target	100° C
Total Hg inventory	10 t
Pump power	50 kW



MERIT –Mercury Intense Target

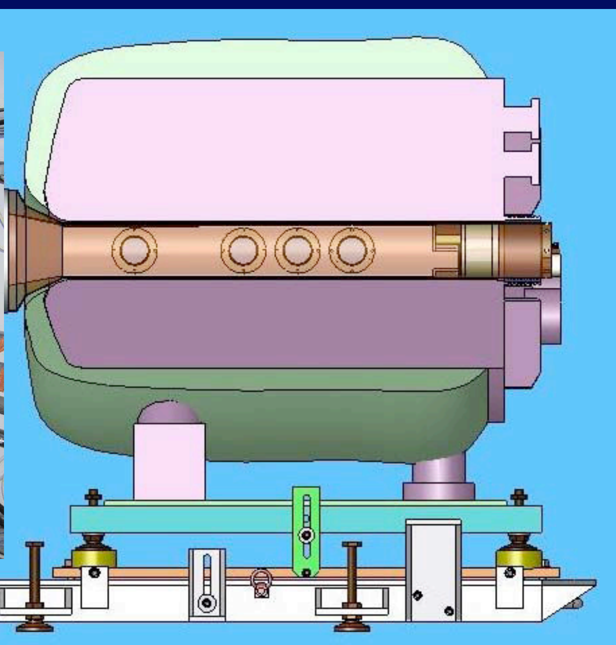
Test of Hg-Jet target in (pulsed) magnetic field (15T)

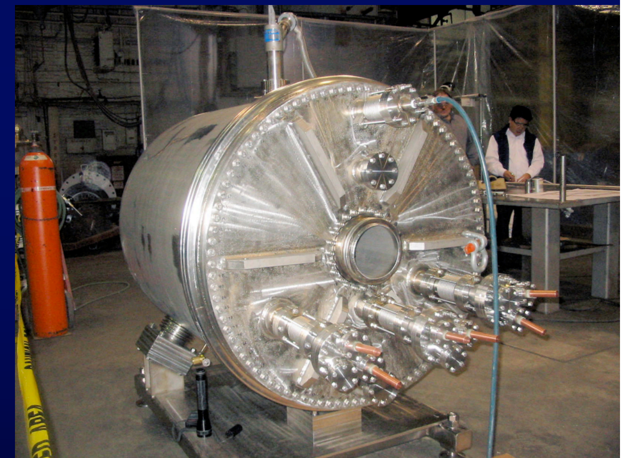
Submitted to CERN April, 2004 (approved April 2005)

Located in TT2A tunnel to ISR, in nTOF beam line

First beam end 2007

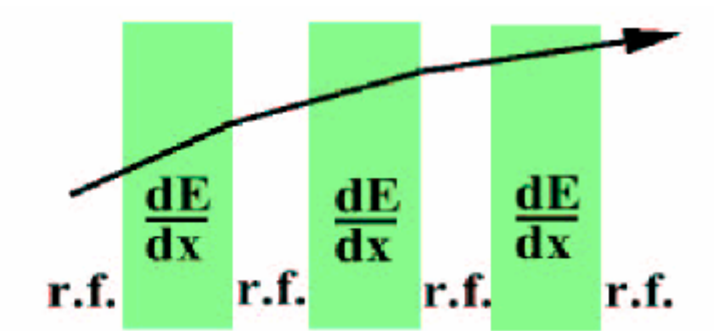
Intensity is equivalent tp 4MW for 50 Hz operation at 24 GeV





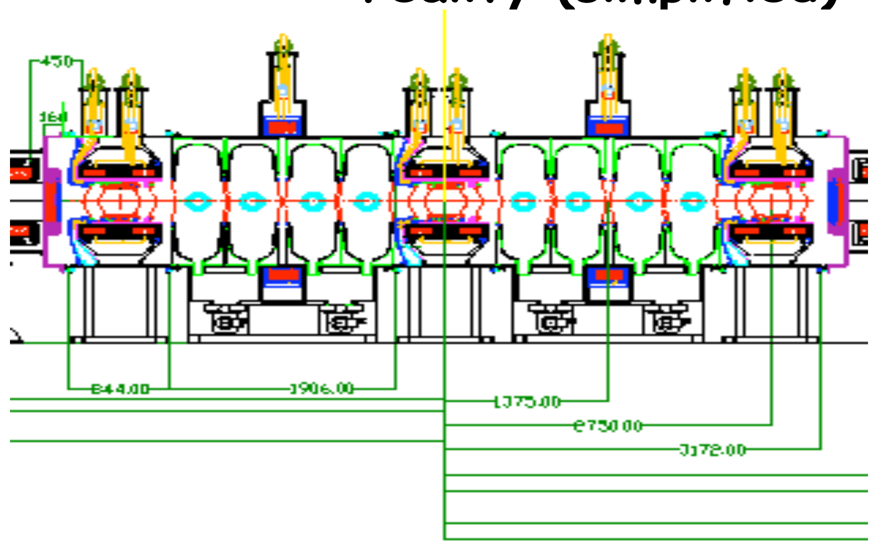
IONIZATION COOLING

principle:



this will surely work..!

reality (simplified)



Front elevation of the Cooling Channel

….maybe…

Cooling is necessary for Neutrino Factory and crucial for Muon Collider.
Delicate technology and integration problem
Need to build a realistic prototype and verify that it works (i.e. cools a beam)

Can it be built? Operate reliably? What performance can one get?
Difficulty: affordable prototype of cooling section only cools beam by 10%,
while standard emittance measurements barely achieve this precision.
Solution: measure the beam particle-by-particle

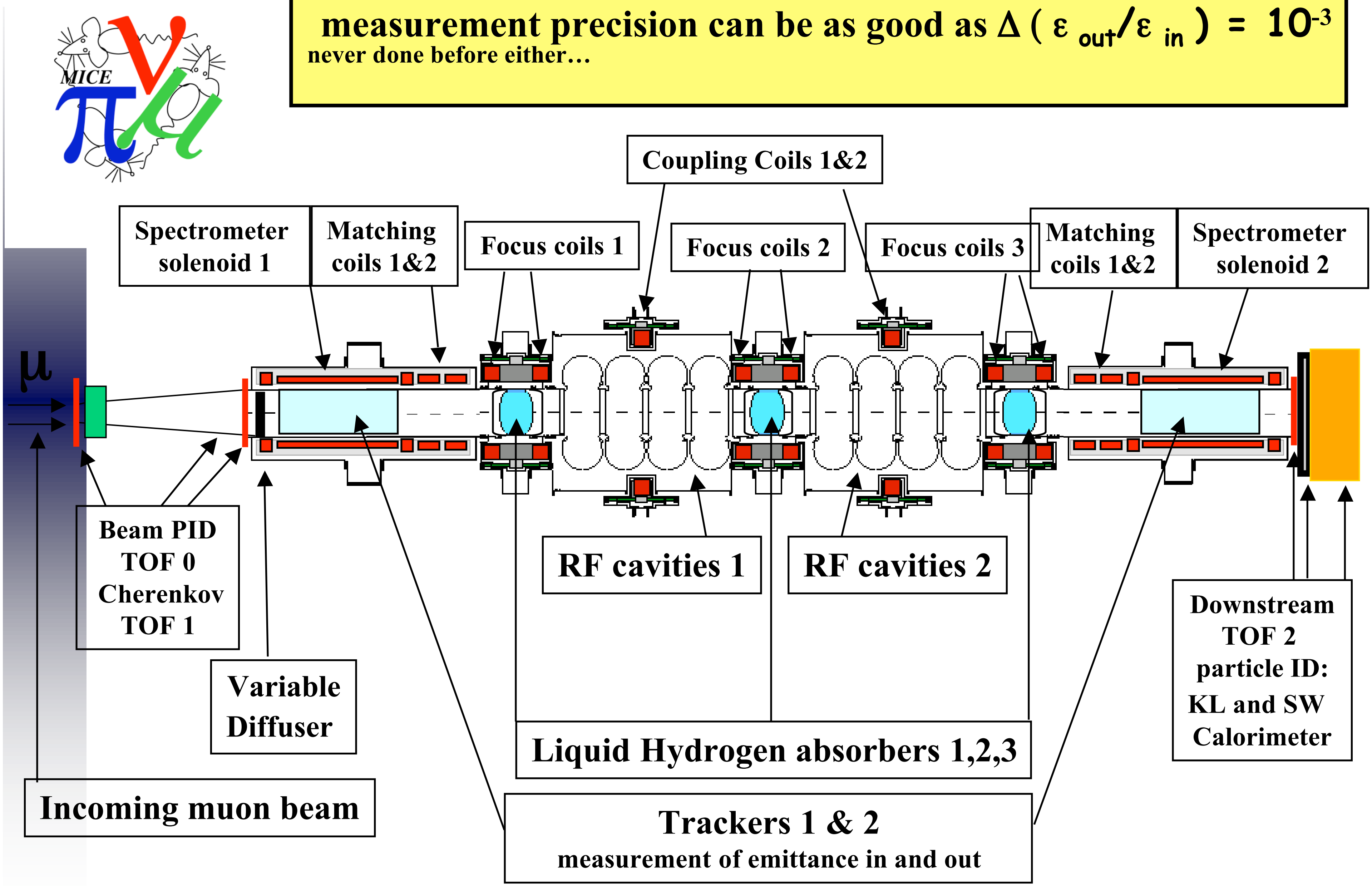
state-of-the-art particle physics instrumentation
will test state-of-the-art accelerator technology.

10% cooling of 200 MeV/c muons requires ~ 20 MV of RF

single particle measurements =>

measurement precision can be as good as $\Delta(\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

never done before either…



Challenges of MICE:

(these things have never been done before)

1. Operate RF cavities of relatively low frequency (201 MHz) at high gradient (nominal 8MV/m in MICE, 16 MV/m with 8 MW and LN2 cooled RF cavities) in highly inhomogeneous magnetic fields (1-3 T)
   dark currents (can heat up LH_2), breakdowns

2. Hydrogen safety (substantial amounts of LH_2 in vicinity of RF cavities)

3. Emittance measurement to relative precision of 10^{-3} in environment of RF bkg
   requires
   low mass (low multiple scattering) and precise tracker
   fast and redundant to fight dark-current-induced background
   precision Time-of-Flight for particle phase determination ($\pm 3.6^0$ = 50 ps)
   complete set of PID detectors to eliminate beam pions and decay electrons

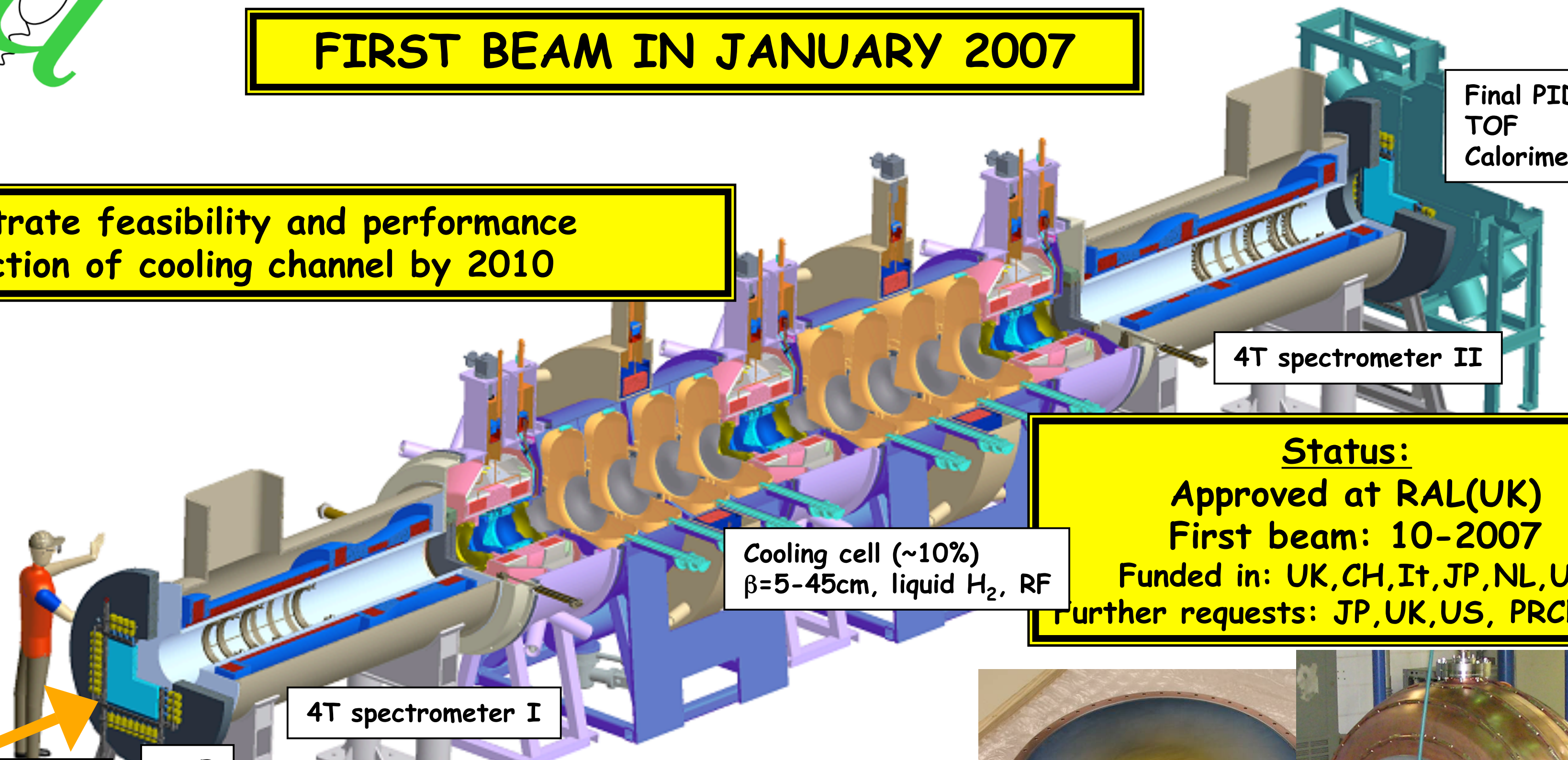
and…

4. Obtaining (substantial) funding for R&D towards a facility that is not (yet) in the plans of a major lab

Muon Ionization Cooling Experiment MICE

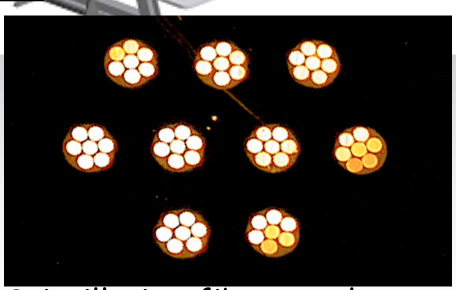
FIRST BEAM IN JANUARY 2007

Demonstrate feasibility and performance of a section of cooling channel by 2010



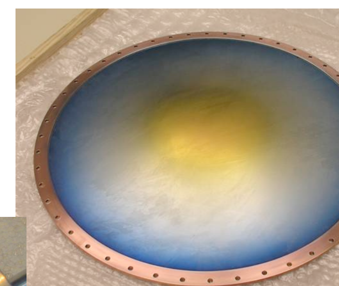
<u>Status:</u>
Approved at RAL(UK)
First beam: 10-2007
Funded in: UK,CH,It,JP,NL,US
Further requests: JP,UK,US, PRChina…

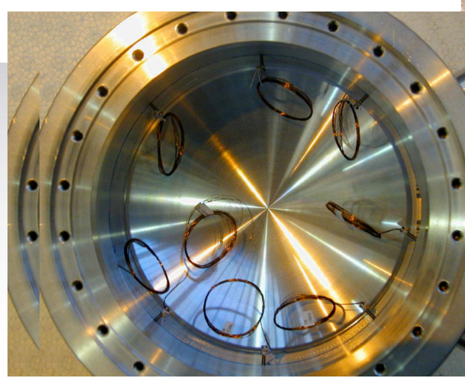
<u>construction</u>

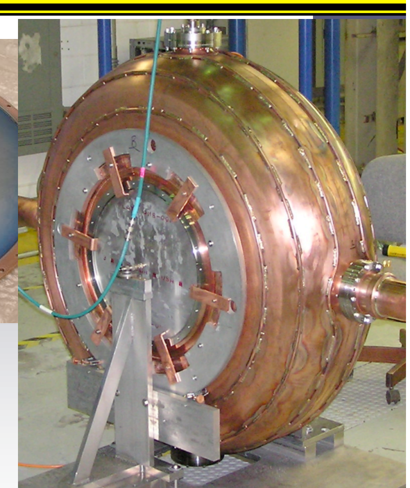


Scintillating-fiber tracker

Liquid-hydrogen absorbers

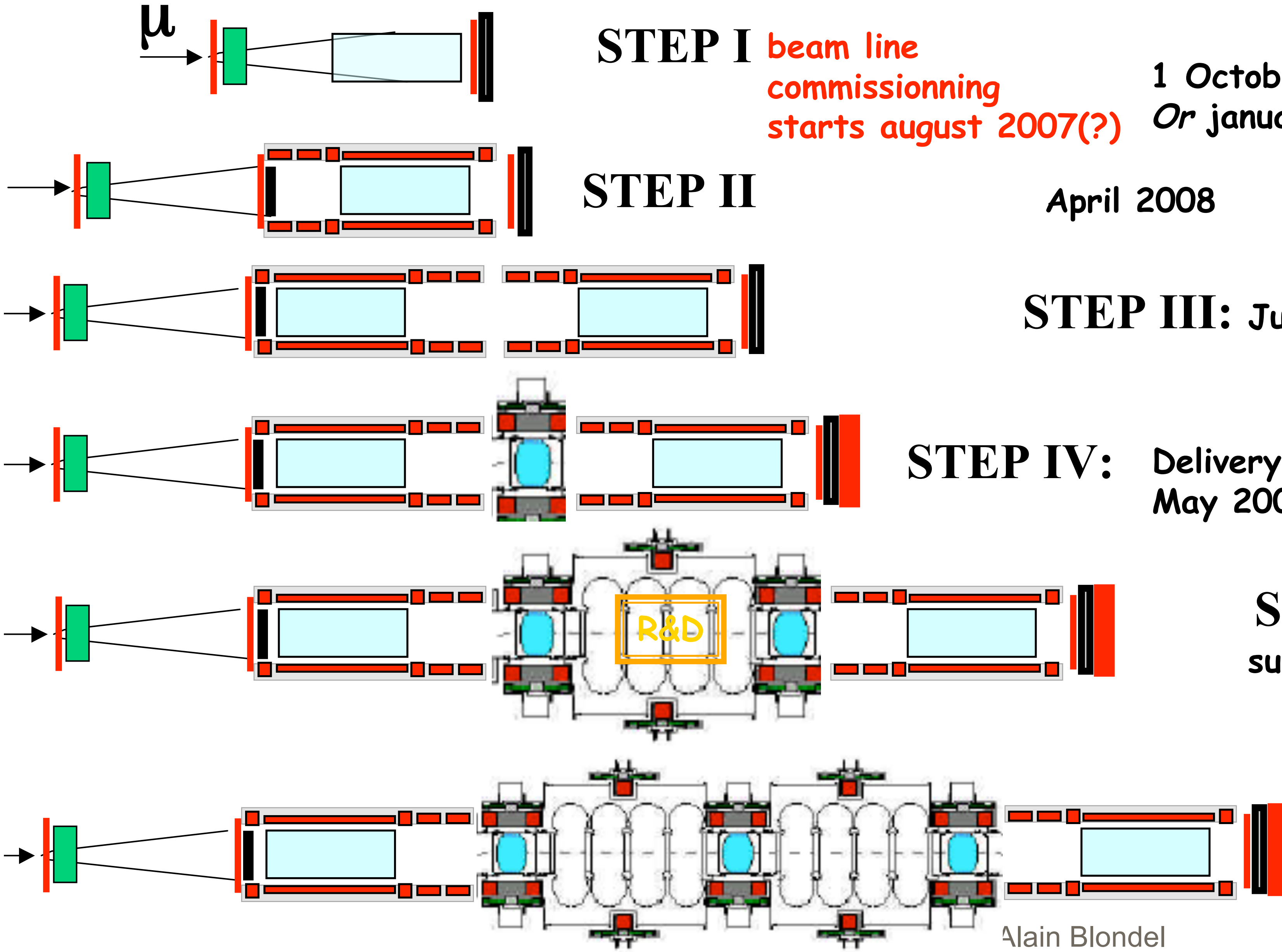






200MHz RF cavity with beryllium windows

Aspirational MICE Schedule as of june 2007



STEP I beam line commissionning starts august 2007(?)

1 October 2007
Or january 2008

STEP II

April 2008

STEP III: July 2008

STEP IV: Delivery of 1st FC
May 2009

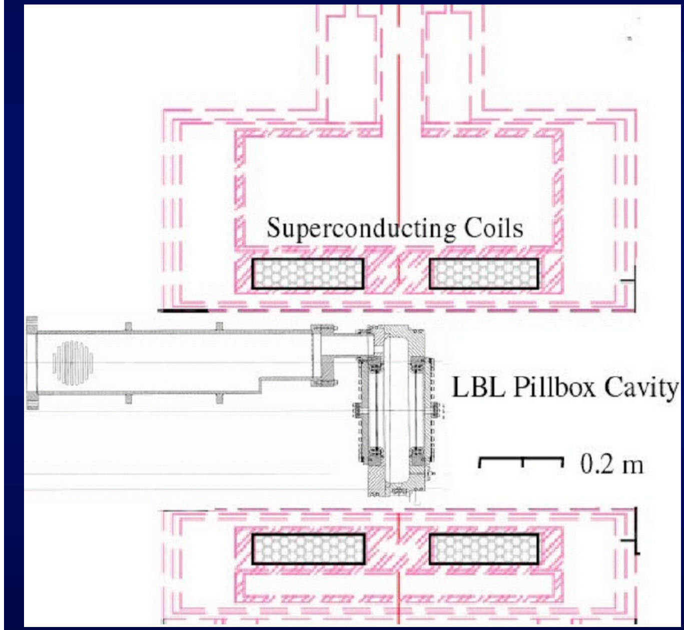
STEP V:
summer 2009

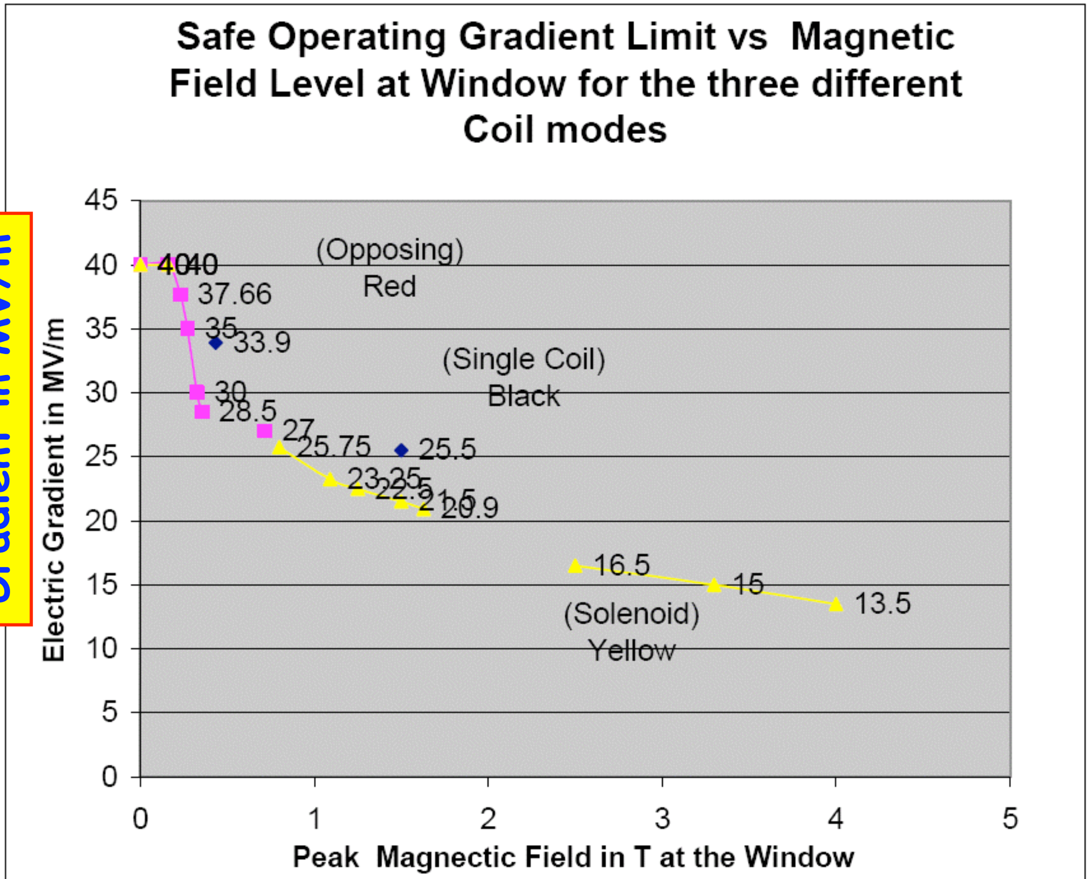
STEP VI
end 2009

Phase I of RF Cavity Closed Cell Magnetic Field Studies (805 MHz)

Max stable gradient degrades quickly with B field

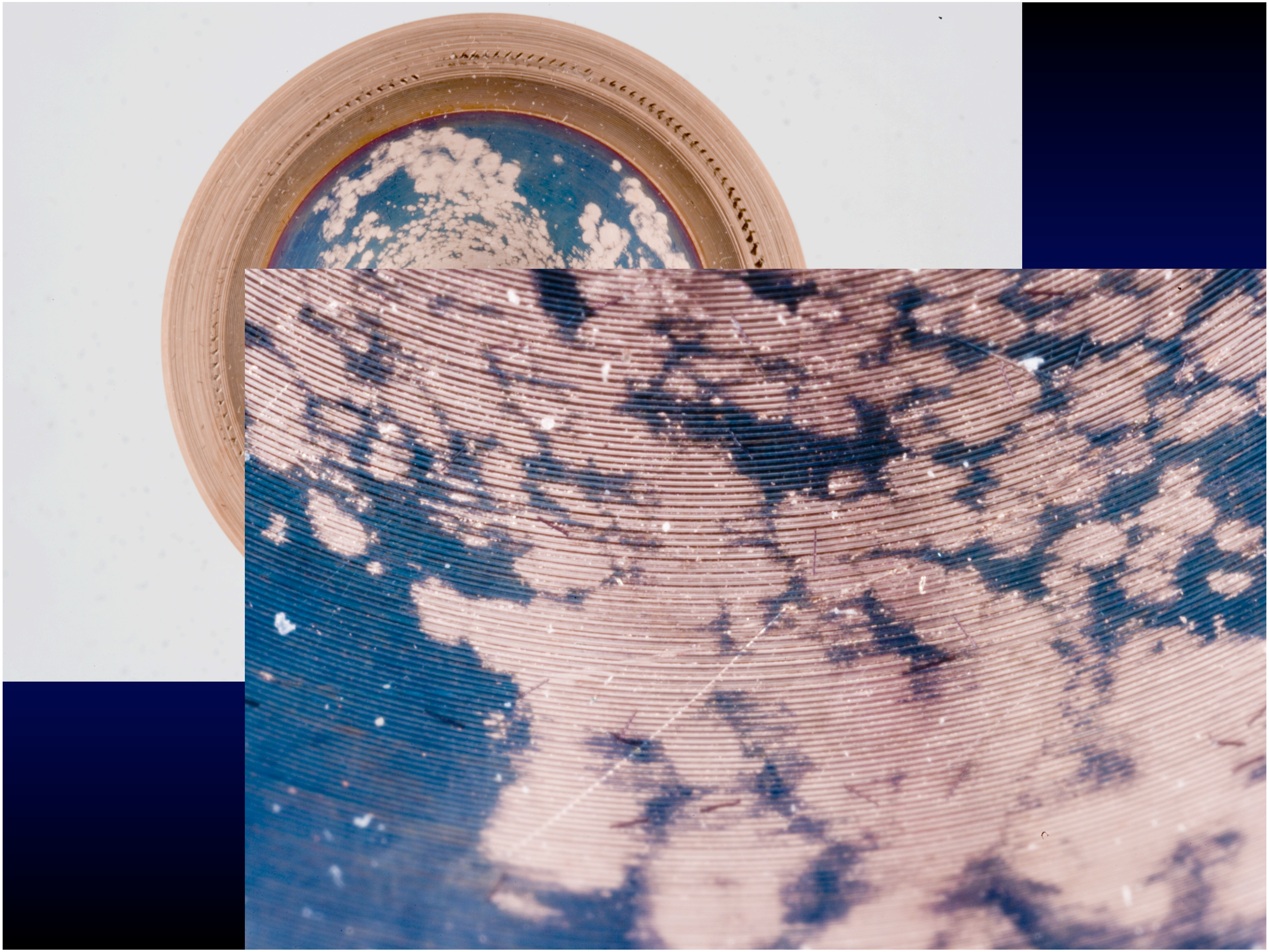
Sparking limits max gradient   Copper surfaces seem to be the the problem





Gradient in MV/m

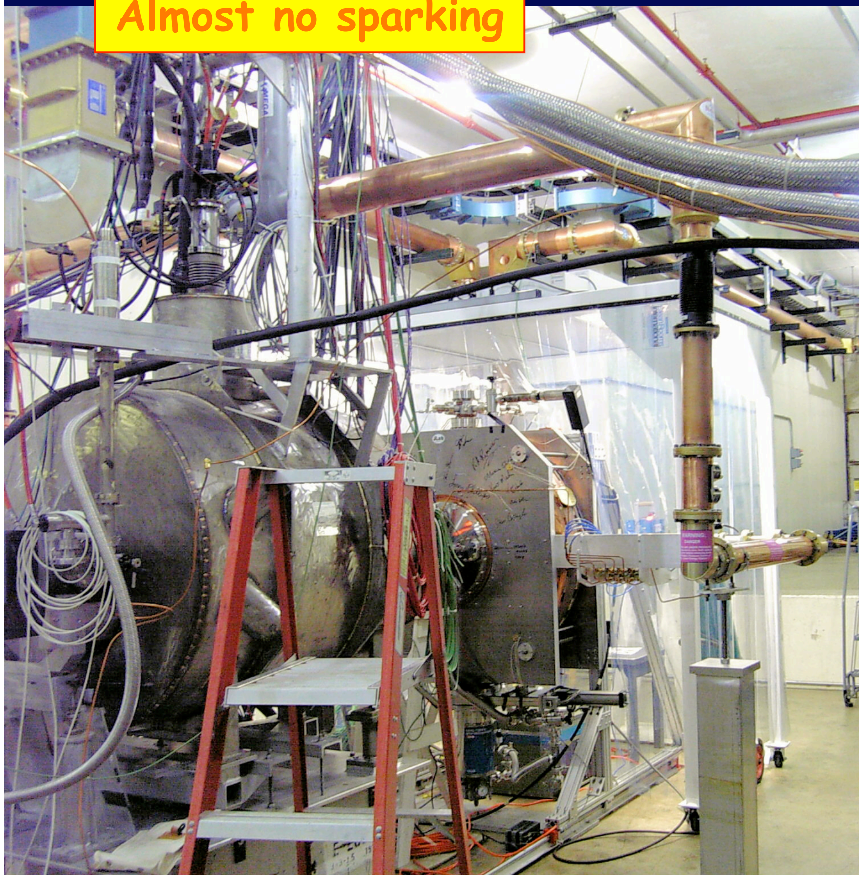
Peak Magnetic Field in T at the Window

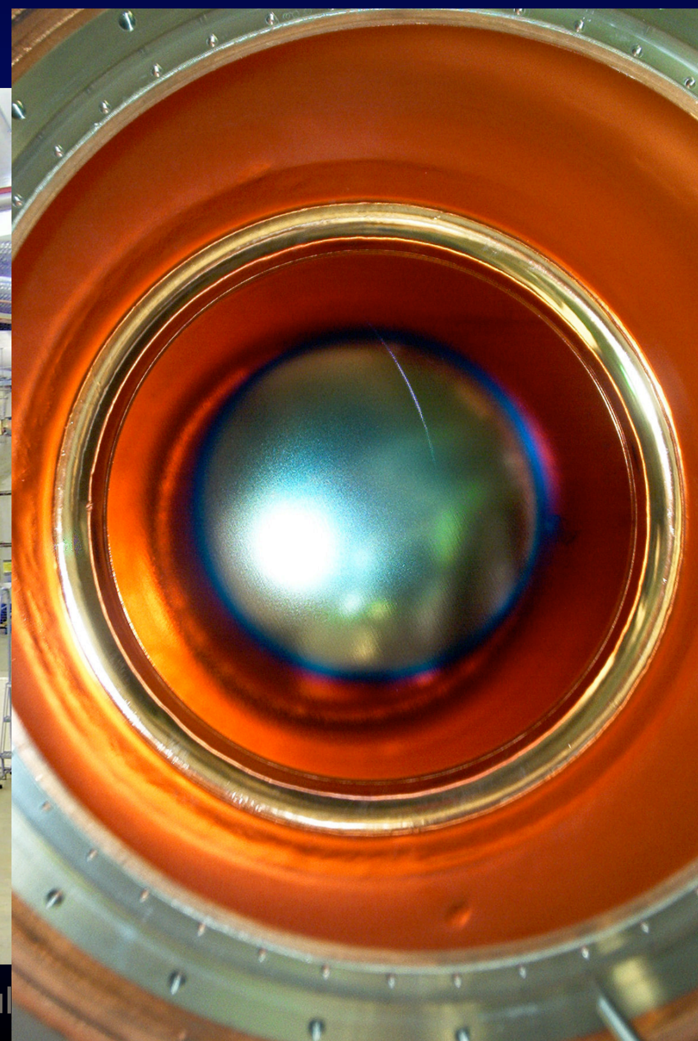


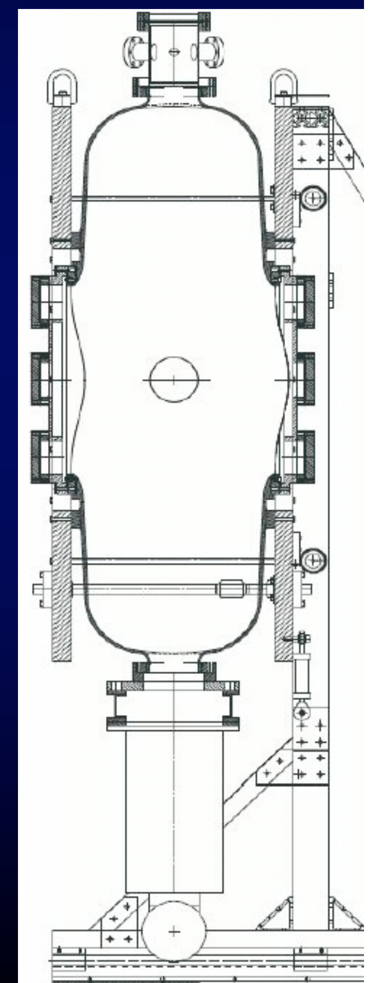
RF R&D – 201 MHz Cavity

The 201 MHz Cavity has now been tested to design gradient - 16MV/m at B=0 and at B= a few hundred Gauss

Did Not Condition!
Almost no sparking







Berylium window For RF cavities

Note 'violin' shape

CONCLUSIONS

Neutrino factory and beta beams offer clean electron neutrino beams with well defined flavour and flux. These will be necessary for high sensitivity or high precision neutrino studies.

Each of the schemes offers advantages:
-- matter effects and tau channel (Nufact) or synergies with superbeam and proton decay/Supernova search (BB)
-- low energy nuclear effects are difficult to master (BB)
-- mature design (Nufact) vs new technological inventions (BB)
-- well defined hurdles (Nufact) vs principle uncertainties (BB)
-- use of existing infrastructures (BB) vs path to muon collider (NuFact)

-- decision point should be around 2012 and by then both schemes should be thoroughly studied. Decision will depend to some extent on the value of θ_{13}

-- Enthusiastic (but small) communities are proceeding with the R&D experiments